PERFORMANCE OF TWO AGRO-HYDROLOGICAL MODELS IN SIMULATING SOIL WATER BALANCE OF A RAINFED MAIZE FIELD

BY

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M.Sc./ENG/6776/2011-2012

BEING A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY ZARIA, IN PARTIAL FULFILLMENT OF THE AWARD OF MASTER OF SCIENCE DEGREE IN AGRICULTURAL ENGINEERING.

DEPARTMENT OF AGRICULTURAL ENGINEERING, FACULTY OF ENGINEERING, AHMADU BELLO UNIVERSITY, ZARIA NIGERIA

FEBRUARY, 2015

ABSTRACT

Roles of water balance components in any agro-ecological system are indispensible for most physical and physiological processes within the soil-plant-atmosphere system. The performance of two agro-hydrological models: the Soil-Water-Atmosphere-Plant (SWAP) and Irrigation Scheduling Impact Assessment model (ISIAMOD) in simulating soil water balance components (SWBC) of a cropped field under rainfed condition, was studied in a sandy clay loam soil at the Research field of the Department of Agricultural Engineering, Ahmadu Bello University, Samaru, Nigeria. A field experiment consisting of nine sets of weighing-type mini-lysimeter installed in a field of size 0.053 ha was used in the study. The experiment consisting of three treatments replicated three times. The three treatments comprise of cropped lysimeter set-up covered with plastic mulch (polythene) to measure transpiration (T) process, no-mulch cropped lysimeter setup to measure evapotranspiration (ET) process and no-cropped lysimeter set-ups to measure the process of evaporation (E). The lysimeters and the surrounding field were planted with Sammaz-28 Maize variety. The components of soil water balance which include ET, T, E, runoff (R_{off}) and deep percolation (D_p) were measured directly from the lysimeters. To complement the measurement of ET from the lysimeter, soil moisture depletion study was also carried on the field by installing gypsum blocks at different depths to measure soil moisture. The results showed that the performance of the two models in simulating soil water balance components as compared to the field measured values was satisfactory based on the outcome of the statistical indicators used. The statistical indicators used to compare the performance of the models are coefficient of residual mass (CRM), modelling efficiency (EF) and root mean square error (RMSE). CRM showed that ISIAMOD has the tendency of underestimating the ET, T, and $E_{crop}$by a value which ranges from 2.5 to 6.0% while SWAP has the tendency of overestimating the same components which ranges from 2.0 to 9%. The modeling efficiencies of the two models range from 84 to 90%, except for evaporation processes which ranges from of 54 to 62%. The RMSE of the two models ranges from 0.29 to 0.86. They both simulated the seasonal run-off and drainage well. The results show that two models can be used for determination of soil water balance components of cropped soil and for analyzing a better water management option for agricultural production.

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FEBRUARY, 2015

DECLARATION

I declare that the work in this thesis entitled "PERFORMANCE OF TWO AGRO-HYDROLOGICAL MODELS IN SIMULATING SOIL WATER BALANCE OF A RAIN-FED MAIZE FIELD" has been carried out by me in the Department of Agricultural Engineering under the supervision of Prof. H. E. Igbadun and Prof. O. J. Mudiare. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

AliyuSalisuIBRAHIM …… ……

M.Sc./ENG/6776/2011-2012 Signature Date

CERTIFICATION

This thesis entitled PERFORMANCE OF TWO AGRO-HYDROLOGICAL MODELS IN SIMULATING SOIL WATER BALANCE OF A RAIN-FED MAIZE FIELD by AliyuSalisu IBRAHIM meets the regulations governing the award of the degree of masters in Agricultural Engineering (Soil and Water option) of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

PROF. H.E. IGBADUN …… ……..……
Chairman, Supervisory Committee (Signature) (Date)

PROF. O.J. MUDIARE …… …… ……
Member, Supervisory Committee (Signature) (Date)

PROF. D.D. YUSUF …….
Head of Department (Signature) (Date)

Prof. A. Z. Hassan …… ..…….
Dean, School of Postgraduate Studies (Signature) (Date)

DEDICATION

To my parents, Malam Ibrahim Salisu (Late) and Malama Fatima Ibrahim Musa, and my friend Abdullahi Mohammad Sani, for their sacrifice, love, support and encouragement throughout the programme.

ACKNOWLEDGMENT

There is no self-made man!!! Our lives are the sum totals of the inputs of others who have contributed in one way or the other in influencing and shaping of our life, and allow us to stand on their shoulder to see the distant a far. My profound gratitude goes to my supervisors, Prof. H. E Igbadun and Prof. O. J. Mudiare, for their untiring efforts, encouragements, meaningful suggestions, corrections and criticisms rendered during the course of this experimental work and the write-up of this thesis.I would like to express my sincere thanks to the Head of my Department, Prof. D. D. Yusuf, for providing the necessary facilities which led to the successful completion of the work.I am also indebted to the non-academic staff of the Department; Mrs. J.O. Ichi, Mrs. L. L. Musa, B. P. Gwajack, Mal. Hassan Usman Mohammad, Mrs. Othman and Mal. Lalaye, for their assistance during the conduct of the experiment.

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ABSTRACT

Roles of water balance components in any agro-ecological system are indispensible for most physical and physiological processes within the soil-plant-atmosphere system. The performance of two agro-hydrological models: the Soil-Water-Atmosphere-Plant (SWAP) and Irrigation Scheduling Impact Assessment model (ISIAMOD) in simulating soil water balance components (SWBC) of a cropped field under rainfed condition, was studied in a sandy clay loam soil at the Research field of the Department of Agricultural Engineering, Ahmadu Bello University, Samaru, Nigeria. A field experiment consisting of nine sets of weighing-type mini-lysimeter installed in a field of size 0.053ha was used in the study. The experiment consisting of three treatments replicated three times. The three treatments comprise of cropped lysimeter set-up covered with plastic mulch (polythene) to measure transpiration (T) process, no-mulch cropped lysimeter setup to measure evapotranspiration (ET) process and no-cropped lysimeter set-ups to measure the process of evaporation (E). The lysimeters and the surrounding field were planted with Sammaz-28 Maize variety. The components of soil water balance which include ET, T,E, runoff (R_{off}) and deep percolation (D_p) were measured directly from the lysimeters. To complement the measurement of ET from the lysimeter, soil moisture depletion study was also carried on the field by installing gypsum blocks at different depths to measure soil moisture. The results showed that the performance of the two models in simulating soil water balance components as compared to the field measured values was satisfactory based on the outcome of the statistical indicators used. The statistical indicators used to compare the performance of the models are coefficient of residual mass (CRM), modelling efficiency (EF) and root mean square error (RMSE). CRM showed that ISIAMOD has the tendency of underestimating the ET, T, and $E_{crop}$by a value which ranges from 2.5 to 6.0% while SWAP has the tendency of overestimating the same components which ranges from 2.0 to 9%. The modeling efficiencies of the two models range from 84 to 90%, except for evaporation processes which ranges from of 54 to 62%. The RMSE of the two models ranges from 0.29 to 0.86. They both simulated the seasonal run-off and drainage well. The results show that two models can be used for determination of soil water balance components of cropped soil and for analyzing a better water management option for agricultural production.

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CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Water balance components in any agro-ecological system are indispensible for most physical and physiological processes within the soil-plant-atmosphere system, especially in arid and semi-arid regions. Quantitative water balance information is required for the development of efficient method of soil water management (Odofin, *et al*., 2012). The knowledge of the circulation of water in and out of the soil mass and especially in a cropped field is very crucial in the planning and operation of various soil and water management strategies. A good understanding of all the aspect of soil hydrological balance (soil water balance), that is, rainfall and or irrigation, water stored in the soil, and water losses from cropped soil due to evapotranspiration, deep percolation and runoff is of importance to appreciate the role of various soil and water management strategies in solving environmental problems and increasing agricultural production. It is a very vital tool in estimating the water need of crops (Zoabeida, 2012; Federer, 1996), irrigation scheduling by soil water accounting under different scenario (Crookston, 2011; Igbadun, 2008). Besides planning of irrigation systems, knowledge of soil water balance and hence crop water use is required when planning the various soil and water management structures such as: erosion control structures, planning and design of water harvesting structures and other soil moisture conservation techniques both during rainy and dry seasons.

Soil water balance (accounting) can be likened to a financial statement of income and expenditure. It is an account of all quantities of water added to " a control volume of soil" through rainfall, irrigation or capillary rise from shallow ground water, and expended

through the processes of evapotranspiration, runoff and deep percolation, and that stored in the given "control volume of soil" during a given period of time. With the help of soil water balance equation, one can identify periods of soil water stress or excesses which may adversely affect crop performance. Positive water balance indicates the availability of water in the soil, while negative water balance gives an estimate of water deficit in the soil, or even the region when whole catchment is considered. This helps in adopting appropriate management practices to alleviate water shortage constraint and increase the crop yields. The values of soil water balance can be valuable indicators for assessing the prospect of growing crops under rain-fed condition and also estimating the additional water need for a region when water balance becomes negative.

1.2 Statement of the Problem

The methods generally used for determining the components of soil water balance can be grouped into direct and indirect methods. The direct methods involve experimentation and in-situ measurements, which can be laboratory or field-based. This can be accomplished either by using a lysimeter or by runoff plot study of the changes in soil moisture content and hydraulic characteristics of a vertical soil profile. A lysimeter is a device in which the experimental soil is placed in a container and separated hydrologically from the surrounding soil (Majumdar, 2006). The lysimetric methods are widely used because all the components of water balance can be obtained directly. These components of the soil water balance can also be obtained using a runoff plot by monitoring the soil water content and hydraulic characteristics of a soil profile (using soil water meters).

Field experiments in general are expensive and time consuming. Determination of soil water balance is a continuous process because of the fact that, changes in land (soil)

management systems alter the soil water balance components quantitatively. For this reasons, the definition of reliable mathematical methods for estimating soil water balance in areas where the amount of available information is limited remains a key concern. One way to overcome these field experimental problems is the use of mathematical simulation models. These constitute the indirect method of estimating soil water balance components. Models can be used objectively to analyse climatic data and to extrapolate experimental results from short-term trials over a period of many years. It can also take account of climate variability. There are several models for estimating and predicting soil water balance, among which are the CropSyst (Stockle and Nelson, 1996), SWAP (van Dam *et al.*, 1997), ISIAMOD (Igbadun, 2006), and APSIM (McCown*et al.,* 1996). Although, the developers have reported reliable performance of these models at the location they were developed or used (van Dam, 1997; Igbadun, 2007; Probert*et al.,* 1998), there is always a need for independent evaluations of these models before usingthem under different fields and climatic conditions. Since there is no single model that can claim universal applicability, and the choice of a model to solve a problem largely depends on the nature of the problem at hand as well as data availability in the research area, it is always necessary to evaluate them before using. This work evaluate the performance of two agro-hydrological models: SWAP (Soil-Water-Atmosphere-Plant) and ISIAMOD (Irrigation Scheduling Impact Assessment Model) in simulating soil water components of a maized cropped field under rainfed condition in Samaru, Zaria-Nigeria. Performance evaluation of any agro-hydrological model in simulating a given data has to do with the comparison of the models' simulated values with the values obtained through the use of the direct method (classical method) to serve as a reference values for comparison with the model output.

1.3 Justification

Maize is popularly grown in the research area and serves as the major food. It can be processed to produce other varieties of foods. Most of the cereal crops (maize, sorghum, etc.) farming activities in the research area are largely during rainy season. Studies on soil water balance of crops under rain-fed condition in this area are scarce, except for few works. The few include the works by Michael (2011) and Aworidhe (2011), on crop water requirement of groundnut, and maize crop evapotranspiration estimation, respectively. Maize is the fifth most important commodity in Nigeria in terms of production volume in the year 2005 to 2010, and characterized by an increasing trends over the period (Cadoni and Angelucci, 2013). More so, Nigeria is the tenth largest producer in the world and largest producer in Africa followed by South Africa (IITA, 2003). Research works on the use of agro-hydrological models have been conducted in Asia, Europe, U.S, few African countries (Tanzania, Namibia, etc.). However, studies on the application of these models in water management in Nigeria, and in particular the study area under rain-fed condition is yet to be fully explored. This when accomplished mightserve as water management tool for the various farming activities available in Zaria (i.e., the selected research site), and also the neighbouring states under the same geo-climatic zone (that is, within the same Northern Guinea Savannah). Use of simulation reduces drudgery and time wasting in field experimentation to establish a water management option. It can also serve for research purposes by the university community.

The knowledge of soil water balance is very vital under crop water management strategy that involves growing of different crops of different rooting system (e.g. crops and shrubs) on a particular field at the same time. This is because of their different water

extraction pattern due to different rooting system. As such, having a model that can simulate the soil water balance, as against the tedious direct methods is an added advantage. Most of the information on soil water balance available in literature is largely obtained from irrigation studies, which were developed during dry seasons (Igbadun, 2012). It is very likely that under rain-fed conditions, such information with respect to the same cropped field might differ. This is because; the micro-climate during the wet season differs from that of the dry season. It is most expected that the various soil water balance components are likely to differ because of difference in atmospheric water demand of the same crop with respect to seasonal variation (Igbadun, 2012).

1.4 Objective of the Study

The aim of this research work is to evaluate the performance of two computer-based agro-hydrological models (SWAP and ISIAMOD) in simulating soil water balance components of a maize cropped field under rain-fed condition.

The specific objectives are to:

(i) Estimates the soil water balance components (evaporation, transpiration, drainage, runoff, and precipitation) of a rain-fed maize crop field using mini-lysimeters;

(ii) Simulate the soil water balance of the same cropped field using SWAP and ISIAMOD models.

(iii) Compare the performances of the two models in predicting field measured data.

CHAPTER TWO

LITERATURE REVIEW

2.1 Agro-hydrological Models

A mathematical model is a set of equations that represent interconnections in a system, and be worked out either by hand or by using a computer. Mathematical models are described based on the nature of the equation which have been used to described, or represent the nature of the system being modeled. In this regards, mathematical models are classified as theoretical (or conceptual), empirical and semi-empirical models. Empirical models are data-driven, mainly, based on data used and do not explain the mechanism of the system. It is built based on the general laws of the system but is a condensed representation of the system. It sets-out principally to describe the relation between depended and independent variable(s). Theoretical or conceptual models are theory driven. They are process based (or mechanistic) models that include a set of general laws or theoretical principles. It could be physically based if all the governing principles are well known and can be described by equation of mathematical physics. Semi-empirical models on the other hand are developed from combination of statistical (empirical) relationship and theoretical (conceptual) expressions. A mechanistic model assumes that a complex system can be understood by examining the working of its individual parts and the manner in which they are coupled. A process mechanistic model is an elaborate and practically complete description of the physics, chemistry and biological principles involved in a process. For instance, photosynthesis, green or dry matter production, soil water uptake and solute transport by the root system, etc. However, as put forward by Muthuri (2004), all existing theoretical models simplify the physical system and often include obviously empirical

components. Thus, the distinction between theoretical (conceptual) models is not a clear-cut one.

Agro-hydrological models are water-oriented models that couples hydrological and crop models (van Ittersum*et al*., 2003; Whitehead et al., 1998; Hutchings *et al*., 2004; Duretz*et al*., 2011).The governing equations and underlying theory of the different agro-hydrological models are different. The mathematical formulation, structure and complexity of the crop simulation models are also very different. For some models, empirical or semi-empirical equations were sufficient to describe the processes of interest, while other models include complex mechanistic equations to capture certain crop or soil water response.

Most process-based agro-hydrological simulation models in the field of both rain-fed and irrigated agriculture that are popularly in use for soil and water management are mechanistic models; with some containing a mixture of empirical and mechanistic concepts. They differs mostly on the concepts of soil water dynamics, which ranges from the use of a simple "tipping-bucket" module (or scheme cascading module) to those that solve more complex and vertical algorithms, based on the Richards´ equations. Richards' equation has a clear physical basis at a field scale where the soil can be considered to be a continuum of soil, air and water. In principle, the use of numerical solutions for the Richards´ equation is better for soils below field capacity (Johannes, *et al*., 2011). Cropsyst (Stockleand Nelson, 1996), SWAP (van Dam et al., 1997), ISIAMOD (Igbadun, 2008), AquaCrop (Hsiao, *et al.*, 2009), APSIM (McCown*et al*., 1996), DSSAT (Tsuji *et al.*, 1994), SWATRE (Belman et al., 1983), CERES-maize (Jones and Kiniry, 1986), and EPIC (Williams et al., 1989) are process-based mechanistic models.

For the concept of their soil water dynamics: AquaCrop and ISIAMOD are based on tipping-bucket module, while APSIM and Cropsyst include both the tipping-bucket module and solution of Richard's equation; SWAP and SWATRE are based on solution of Richard's equation; and DSSAT is based on empirical procedures.

2.2 Soil Water Balance

Water balance is simply a statement of the law of conservation of matter. This means that the moisture content of a given "control soil volume" cannot increase without addition from outside through rainfall and or irrigation, nor can it diminish unless transported to atmosphere by evaporation, run-off or by deep percolation beyond root zone through drainage (Hillel, 1971). In its simplest form, the soil water balance equation states that, changes in volumetric water content of soil over a period of time are equal to the difference between the amount of water added ('W_{in}') and the amount of water withdrawn ('W_{out}')during the same period.

$$\Delta W = W_{in} - W_{out} \quad \text{..... (2.1)}$$

Where;

ΔW is change in volumetric moisture content over the time laps. The change in volumetric moisture content (ΔW) could be positive if gain exceeds losses; and negative when losses exceed gains. The terms in the equation are normally expressed in unit of volume per unit area (mm). For a given soil volume, the water gains (W_{in}) and losses (W_{out}) can be itemized as follows: the amount water added 'W_{in}' may be precipitation , P, irrigation, $I_{r,}$ runoff from other field, R_{in}, or contribution from groundwater through capillary rise G (if not very far from the root zone).

$W_{in} = P + I_r + G + R_{in}$…….…….. (2.2)

On the other hand, the losses of water 'W_{out}' may be due to the processes of runoff out of the experimental field, R_{out}, deep drainage (or deep percolation), D_p, soil evaporation, E, and crop transpiration, T (if the area is cropped).

$W_{out} = R_{out} + D_p + E + T$ …….. (2.3)

During the rainy season, the rainfall interception component has to be included here, except if neglected. The integral form of soil water balance equation summed over the time step is presented as:

$\Delta W = P + I_r + G + R_{in} - (R_{out} + D_P + E + T)$ ……..... (2.4)

Figure 2.1 presents the various components of soil water balance for a cropped field.

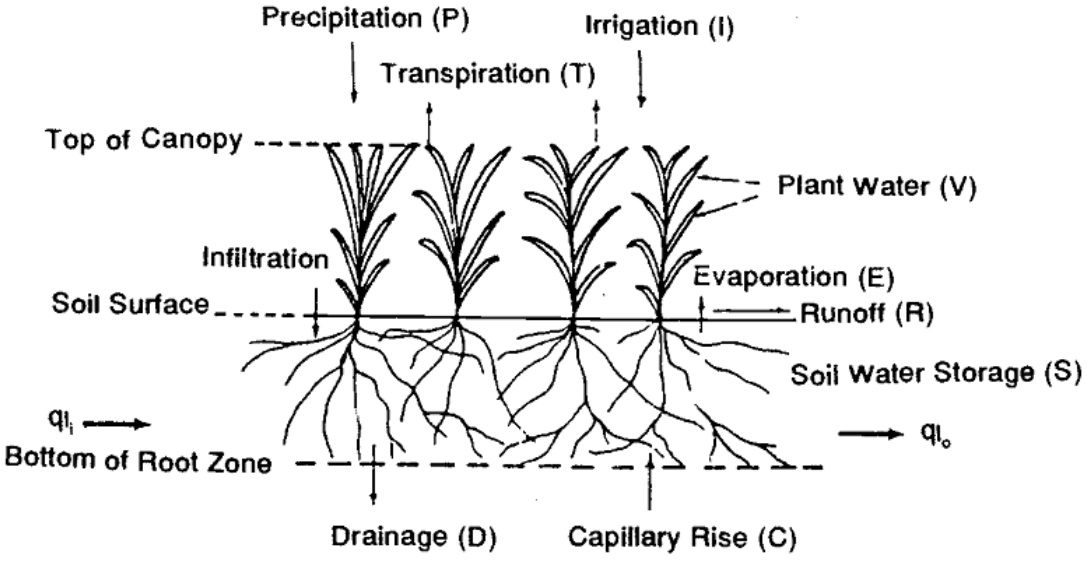


Figure 2.1: Schematic presentation of soil water balance components (Hartmann, 1990)

Measurement of the components of the soil water balance equation is essential to maintaining a water budget. They can be measured directly in the field with a lysimeter (weighing or non-weighing type) or using a runoff plot in the field by the studying changes in water content across a soil profile within the root zone.

2.3 Soil Water Balance Estimation using Lysimeters

Lysimetre is a tank filled with undisturbed or repacked soil and buried permanently or temporally in the ground. The method involves growing crops in lysimeters installed in crop fields to provide the crop environment from which soil/crop parameters are measured. Measurement of different components of soil water balance such as; water added to lysimeter through precipitation and or irrigation, change in soil water storage, and water losses through the processes of evaporation, transpiration, run-off and deep percolation (or deep drainage) can be measured easily. It provides a control volume in which a number of soil water balance components are integrated and measured directly and also enhances the understanding of dynamic of soil water and nutrients in the ecosystems.

Lysimeters are used as tools to analyze the relationships that existed among soil, water, and plants, as well as in water quality studies. A lysimeter consists of an isolated container of soil whose water movement characteristics can be studied and measured directly. When a crop is planted at the ground level of the lysimeter, water use (evaporation and transpiration, or evapotranspiration) can be determined through water balance techniques. Lysimeters used for evapotranspiration (ET) research are typically classified according to their design and use as follows: monolithic or reconstructed soil profiles, weighing or non-weighing designs, and gravity or vacuum drainage designs. Monolithic

lysimeters attempt to preserve existing vegetation and soil properties that can be destroyed by the excavation and filling (Schneider and Howell, 1991) that is done when using reconstructed soil profiles in the container. Weighing lysimeters determine evapotranspiration directly, by the mass balance of the water; non weighing lysimeters indirectly determine ET using the volumetric soil-water balance in the container (Howell *et al.,* 1991). That is, the weighing-type lysimeter, measure soil water balance components directly by measuring the changes in weight of an isolated soil volume. The soil water balance components are calculated from the changes in weight of the lysimeter tank, and adjusted to account for weight changes caused by factors other than crop water use such as drainage or runoff and water input (Malone *et al.,* 2000).

Large lysimeters are expensive to construct, install and maintain. The use of mini or micro-lysimeter in soil water balance estimation have been used for decades (Clark *et al*., 1984; Rosenthal *et al*., 1985; Wight *et al*.,1986; Dugas and bland, 1989; Isard and Belding, 1989; Uzonwa, 1991). Mini-lysimeters have the advantages that permit measurement of the components of soil water balance from smaller areas; create less disturbance to the environment of interests during installation; and are considerably cheaper to construct, install and to maintain. The method is widely used since all the components of water balance can be obtained, and it remains the only method in which the researcher/experimenter has control over all the components of soil water balance (Wright, 1990; Poss, *et al*., 2004; George, 2005;Vesna, *et al*., 2012; Rafael *et al*., 2011,). Lysimeter is the only hydrological method in which the experimenter/researcher has a complete knowledge of various terms of the soil water balance equation (Lascano, 1991).

2.4 The Use of Agro-Hydrological Models in Soil Water Balance Estimation

Agro-hydrological models are used as decision-support tools to capture the temporal and spatial variability of rainfall, soils, and crops. Some of these models were earlier developed and used within academic context only but later being used in an operational setting for the commercial farmers (e.g., APSIM),while others (e.g., SWAP) where developed for use within an operational or even commercial context (Johannes *et al*., 2011). These models are used in the field of both rain-fed and irrigation to simulate crop growth processes, soil water balance and soil water dynamic within crop rooting zone. Some of the Agro-hydrological models like SWAP simulate ground and surface water. The applications of Agro-hydrological simulation models have been in practice for over three decades (Belmans*et al*., 1983; Qureshi and Madromootooo, 2001; Zhang *et al*., 2002; Igbadun, 2008). Ines *et al* (2001) used the Soil Water Atmosphere Plant (SWAP) model and Decision Support System for Agro-technology Transfer (DSSAT) model to simulate crop growth and soil water balance in Thailand. Igbadun (2006 and 2008) developed and used ISIAMOD to study the impact of irrigation scheduling on yield and soil water balance of maize cropped field. Cavero,*et al* (2000) compared EPICphase, modified EPICphase and CROPWAT models to simulate maize yield under water stress condition (deficit irrigation) Zaragoza, Spain. This work attempts to focus on SWAP (Soil-Water-Atmosphere-Plant simulation model) and ISIAMOD (Irrigation Scheduling Impact Assessment Model) on a maize cropped field under rain-fed condition.

2.4.1 SWAP (Soil-Water-Atmosphere) model

SWAP (Soil-Water-Atmosphere -Plant) model was developed by DLO Winand Staring Centre and Wageningen Agricultural University, and was designed to simulate transport processes at field scale level and during whole growing seasons. The research team include: J.C. van Dam, J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. van Walsum, P. Groenendijk and C.A. van Diepen, 1997. SWAP model is successor of (has been developed from) the agro-hydrological models: SWATRE and SWACROP and some of its numerous derivations. For instance, SWASALT for salt transport and FLOCR for shrinking and swelling clay soils are incorporated into it. The new model version (2.0), took advantage of the experiences gained with the existing SWATRE versions. The model, SWAP, integrate water flow, solute transport and crop growth according to current modeling concepts and simulation techniques. The changes with respect to the well-known SWATRE and SWACROP version are manifold. They include a more versatile numerical solution of the Richards' equation, incorporation of solute and heat transport, attention for soil heterogeneity, shrinking and swelling of clay soils and water repellency, coupling to the detailed WOFOST crop growth model, extension with regional drainage at various levels, and interaction with surface water management. In this way SWAP offers its users a whole range of new possibilities to address both research and practical applications in the field of agriculture, water management and environmental problems. Examples include design and monitoring of field irrigation and drainage systems, rain-fed agriculture production, surface water management, soil and groundwater pollution by salts and pesticides and crop water use and crop production studies. The 2.0d version of SWAP includes also a graphical user interphase for ease of input data files preparation.

SWAP model works based on the numerous interactions that exist between water flow, solute transport, heat flow and plant growth in the soil, to carry out the simulation processes. For example, water fluxes affect the rate of salinization, while salt concentrations affect actual root water uptake rate. Water and salinity stress may affect crop development (depending on the concentration and crop type) and soil cover, which vice versa affects soil evaporation and crop transpiration. Pesticide decomposition is sensitive to soil temperature, which in turn is influenced by soil wetness. In order to carry out the analyses of these kinds of interactions, SWAP solves simultaneously the numerical equations for water flow, solute transport, heat flow and crop growth, and allows the interactions at time step basis. The main feature of the model is the Richards' equation, where the transport of soil water is modeled by combining Darcy's law and the law of continuity. SWAP (2.0d) allows the use of soil hydraulic databases and the simulation of all kinds of management scenarios. The soil hydraulic functions in SWAP are described by the analytical function of Van Genuchten (1980) and Mualem (1976) for soil water retention and hydraulic conductivity. Figure 2.2, shows the schematic overview of SWAP modeled system.

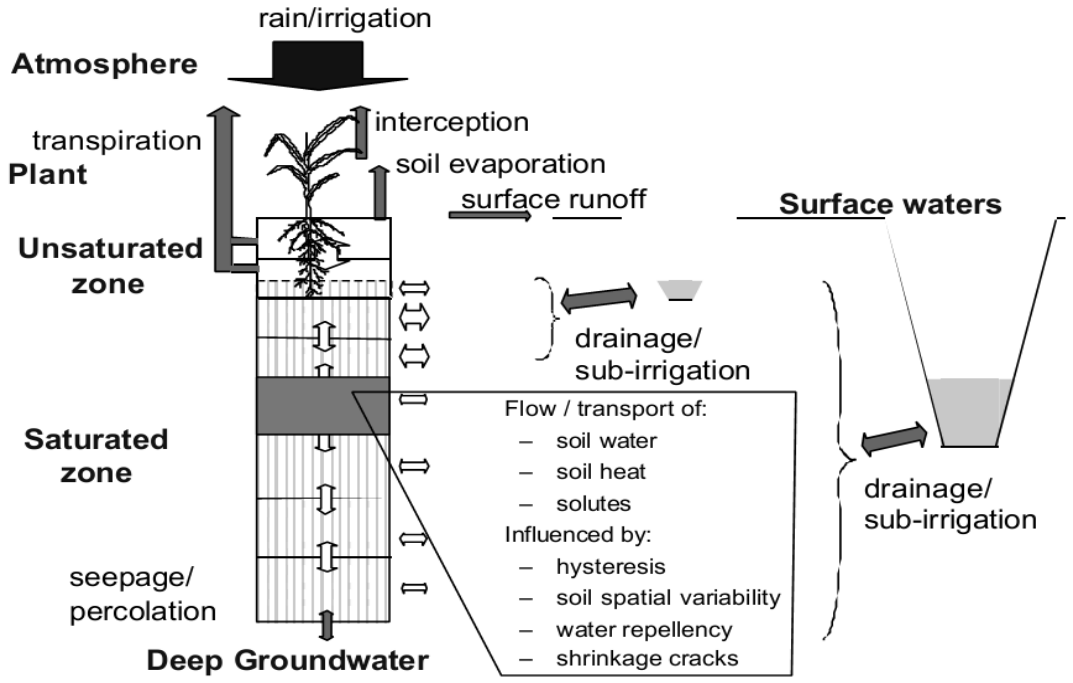


Figure 2.2: A schematic overview of SWAP modeled system (Van Dam et al., 1997).

The soil water balance is solved by considering two boundary conditions (that is, the upper and bottom boundary conditions). The boundaries can either be flux or potential head controlled. The Penman-Moteith equation is used in estimating evapotranspiration. The model uses leaf area index (LAI) to calculate potential transpiration and evaporation.

SWAP contains three crop growth routines modules: a simple module, a detailed module (WOFOST), and the third is the same detailed module attuned to simulate grass growth. The simple module prescribes crop development, independent of external stress factors. The main function is to provide upper boundary condition for soil water movement. The simple crop module is based on the linear production function of Doorebos and Kassam

(1979). The detailed crop module is capable of simulating the growth and development of most crops. The simple module is useful when crop growth does not need to be simulated or when crop growth input data are insufficient. In the simple crop module, the user specify leaf area index or the soil cover fraction, crop height and rooting depth as function of development stage. The development stages are as explained in van Heemst (1988).The development stages can be controled by temperature sum or can be linear in time. The simple module does not calculate the crop potential or actual yield. However, the user may define yield respond factors for various growing stages as function of development stage. Each growing stage 'k' the actual yield $Y_{a,k}$ (Kg/ha) relative to the potential yield $Y_{p,k}$ (Kg/ha) during this growth stage is calculated by:

$$1- \frac{Ya,k}{Yp,k} = K_{y,k}\left(1 - \frac{Ta,k}{Tp,k}\right) \quad \text{.....(2.5)}$$

Where $K_{y,k}$ (-) is the yield respond factor of the growing stage 'k', and $T_{a,k}$ (cm) and $T_{p,k}$ (cm) are the potential and actual transpiration, respectively, during the growing period 'k'.

In case of linear relation between Y_a/Y_p and T_a/T_p during the whole growing period, or when no information is available of the yield response factors as function of development stage D_s for the particular crop, $K_{y,k}$ is specified as 1 for $0<D_s<2$ and one growing stage is specify (k=1).

2.4.1.1 Soil water flow in SWAP model

The water transport in module SWAP is based on Richards' equation, which is a combination of Darcy's law and the continuity equation. A finite difference solution scheme

is used to solve the Richard's equation. The numerical solution requires the definition of initial, upper and lower boundary conditions, as well as the knowledge of the soil hydraulic properties, i.e. the soil water retention curve, and the soil hydraulic conductivity function, K (h). These functions are usually expressed by using the parametric relationships of Van Genuchten (1980) and Mualem (1976). SWAP applies Richards' equation integrally for the unsaturated- saturated zone, including possible transient and perched groundwater levels. For one dimensional vertical flow, darcy's equation can be written as:

$$q = -K(h)\frac{\partial(h+z)}{\partial z} \quad \text{..... (2.6a)}$$

Where q is soil water flux density (positive upward) (cmd^{-1}), K is hydraulic conductivity (cmd^{-1}), h is soil water pressure head (cm) and z is the vertical co-ordinate (cm), taken positive upward.

Water balance considered an infinitely small soil volume result in the continuity equation for soil water:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S(h) \quad \text{……..…….... (2.6b)}$$

Where: θ is volumetric water content (cm^3cm^{-3}), t is time (d) and S is soil water extraction rate by plant root ($cm^3cm^{-3}d^{-1}$).

Combination of equations 2.6a and 2.6b gives the well-known Richards' equation:

$$\frac{\partial\theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(h) \quad \text{…… (2.6c)}$$

Where C is the water capacity ($d\theta/dh$) (cm^{-1})

SWAP solves equation 2.6c numerically, subject to the specified initial and boundary conditions and with known relations betweenθ, h and K. these relationships, which are generally called the hydraulic functions, can be measured directly in the soil, or obtained from the model soil database. The Richards' equation is solved using an implicit finite difference scheme as described by Belmans et al. (1983).

2.4.1.2 Soil water balance components modules in SWAP

(i) Potential evapotranspiration

Daily meteorological data, consisting of air temperature, solar radiation, wind speed and air humidity, are used to calculate daily potential evapotranspiration according to Penman-Monteith (Allen et al., 1998) given by:

$$ET_p = \left[\frac{\frac{\Delta}{\lambda}(R_n - G) + \frac{P_1 \rho_a C_a}{\lambda} \frac{(\ell_s - \ell_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \right] \quad \text{..... (2.7)}$$

where ET_p is potential evapotranspiration rate of the canopy (mm d^{-1}), Δ is slope of the vapour pressure curve (kPa K^{-1}), λ is latent heat of vaporization (J kg^{-1}), R_n is net radiation flux density above the canopy (J m^{-2} d^{-1}), G is soil heat flux density (J m^{-2} d^{-1}),P_1 accounts for unit conversion (= 86400 s d^{-1}), r_a is the air density (kg m^{-3}), C_a is the heat capacity of moist air (J kg^{-1} K^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), r_a is the aerodynamic resistance (s m^{-1}), ɣ is the psychrometric constant (kPa K^{-1}), and r_c is the crop resistance (s m^{-1}).

(ii) Rainfall interception

The Rainfall interception was based on that proposed by von Hoyningen-Hüne (1983), when he measured interception of precipitation for various agricultural crops:

$$P_l = aLAI\left[1 - \frac{1}{1 + \frac{bP_g}{aLAI}}\right] \quad \text{..... (2.8)}$$

Where P_i is intercepted precipitation (cm), LAI is the leaf area index (m^2 m^{-2}), P is gross precipitation (cm), 'a'is an empirical coefficient (taking as 0.25 for most ordinary agricultural crops), and 'b' is the soil cover fraction (LAI/3.0) (-).

(iii)Potential soil evaporation and plant transpiration

SWAP derived potential evaporation rate of a soil under a standing crop E_p (cm d^{-1}) from the Penman-Monteith equation by neglecting the aerodynamic term. This is because the aerodynamic term will be small when the wind velocity near the soil surface is relatively small, which makes the aerodynamic resistance 'r' very large (Ritchie, 1972). Thus, the only source for soil evaporation is net radiation that reaches the soil surface. By assuming that the net radiation inside the canopy decreases according to an exponential function, and that the soil heat flux can be neglected, they (Goudriaan, 1977; Belmans, 1983) derived:

$$E_{\mathrm{p}} = ET_{\mathrm{p}}\, \mathrm{e}^{-\kappa_{\mathrm{gr}} LAI} \quad \text{..... (2.9)}$$

WhereK$_{gr}$ is the extinction coefficient for global solar radiation (-), K$_{gr}$ was taken as 0.39 for common crops. More recent approaches estimate K$_{gr}$ as the product of the extinction coefficient for diffuse visible light, K$_{df}$ (-), which varies with crop type from 0.4 to 1.1, and the extinction coefficient for direct visible light, K$_{dir}$ (-):

$$K_{gr} = K_{df}\ K_{dir} \quad \text{..... (2.10)}$$

In case the leaf area index as function of crop development stage is unknown, the soil cover, SC (-), might be used to determine Ep:

$$E_p = (1 - SC)\ ET_p \quad \text{..... (2.11)}$$

Based on energy considerations, the potential transpiration rate, Tp (cm d-1), equals the potential evapotranspiration rate ETp, corrected for the time needed to evaporate interception water, and minus Ep:

$$T_p = \left(1 - \frac{P_i}{ET_{p0}}\right) ET_p - E_p \qquad \text{with} \qquad T_p \geq 0 \quad \text{..... (2.12)}$$

Where ETp0 is the potential evapotranspiration rate of the wet crop, assuming r crop = 0.

(iv) Actual soil evaporation

In case of a wet soil, soil evaporation is determined by the atmospheric demand and equals potential soil evaporation rate E$_p$. When the soil becomes drier, the soil hydraulic conductivity decreases, which may reduce E$_p$ to a lower actual evaporation rate, E$_a$ (cm d^{-1}).

In SWAP the maximum evaporation rate which the top soil may deliver, E_{max} (cm d^{-1}), is calculated according to Darcy's law:

$$E_{\max} = K_{½}\left(\frac{h_{\text{atm}} - h_1 - z_1}{z_1}\right) \quad \text{..... (2.13)}$$

Where $K_{1/2}$ is the average hydraulic conductivity (cm d^{-1}) between the soil surface and the first node, h_{atm} is the soil water pressure head (cm) in equilibrium with the air relative humidity, h_1 is the soil water pressure head (cm) of the first node, and $Z_1$is the soil depth (cm) at the first node.

(v) Actual plant transpiration

The maximum root water extraction rate, integrated over the rooting depth, is equal to the potential transpiration rate, T_p (cm d-1), which is governed by atmospheric conditions. The potential root water extraction rate at a certain depth, S_p (z) (d^{-1}), may be determined by the root length density, π_{root} (z) (cm cm^{-3}), at this depth as fraction of the total root length density using the equation given by Bouten, (1992):

$$S_{\text{p}}(z) = \frac{\pi_{\text{root}}(z)}{\int_{-D_{\text{root}}}^{0} \pi_{\text{root}}(z)\,\partial z} T_{\text{p}} \quad \text{..... (2.14)}$$

WhereD_{root} is the root layer thickness (cm)

(vi)Surface Water Management (Runoff) in SWAP Model

The interaction between soil water and surface water may consist of surface flow (runoff, run-on and inundation) and subsurface flow (drainage or infiltration). Run-on and

runoff options allow the calculation of a sequence of soil profiles along a slope with runoff. For regional water management analysis the groundwater system may interact with a simplified surface water system. The model may serve as a pre-processing tool for solute modelling. The interaction between soil water and deep groundwater is described by the use of time dependent pressure heads, soil water fluxes or the relation between both. When the SWAP model is applied at field scale level, natural soil heterogeneity may be considered within the field.

2.4.1.3 System Boundary Conditions

The upper boundary conditions are determined by the rates of potential evapotranspiration, irrigation and precipitation. SWAP allows nine different lower boundary conditions which could selected from the graphical interface of the model. These include:

(i) Groundwater level is given;

(ii) Regional bottom flux is given;

(iii) Flux from deeper aquifer is calculated;

(iv) Upward flux calculated as a function of groundwater;

(v) Pressure head of bottom compartment is given;

(vi) Zero flux at the bottom of the profile;

(vii) Free drainage at the bottom of the profile;

(viii) Lysimeter with free drainage and Combination of Cauchy and Derichlet conditions.

Among the above boundary conditions; lysimeter with free drainage was selected as the lower boundary conditions, while the upper boundary condition consisting of climate

input data and rainfall at thetop of the crop canopy was chosen as the upper boundary condition for this work.

2.4.1.4 Basic input and output of SWAP (207d) for soil water balance

The SWAP model requires specification of input data such as weather data, soil parameter, crop parameter and model constant.

i. The general key includes information about the environment (project name, meteorological station name), latitude (in degree), altitude (relative to mean sea level) and timing variable for the simulation.

ii. The Meteorological data Includes the daily meteorological data needed for the simulation of soil water balance: solar radiation, air temperature, air humidity and wind speed.

iii. The crop input contains information of date of crop emergence, harvest date leaf area index (LAI), crop height, rooting as a function development stage and irrigation scheduling. The simple crop model was used here. This is useful if accurate simulation of crop water use is more important than accurate simulation of crop yield.

iv. The soil related data includes information of profile description: number of layers and compartments, soil hydraulic function, soil texture, rooting depth limitation. The boundary condition as given above has to do with the influence of other sources of water to the control volume of soil under study (crop root zone).

The soil water balance outputs from the program are: rainfall and irrigation, and bottom flux or deep percolation, interception, runoff, potential and actual transpiration, and potential and actual evaporation.

2.4.2 ISIAMOD (Irrigation Scheduling Impact Assessment Model)

The ISIAMOD was built using empirical and semi-empirical functions which explain crop growth processes and water dynamic within the crop environment (Igbadun, 2006). ISIAMOD program was written in FORTRAN Power Station version 1.0F and it runs on Microsoft Window environment. The input data files are prepared as text and given names. The model runs on a daily time-step, from crop planting date to crop physiological maturity date. The water dynamic of ISIAMOD includes soil water balance and water management response indices (WMRI). The WMRI are used to explain the impact of an irrigation scheduling decision and are grouped into three: water accounting indices, crop water productivity indices and seasonal relative deficit/losses indices. The indices are generated within the model from the crop yield and soil water balance outputs.

2.4.2.1 Soil water balance module of ISIAMOD

The soil water balance unit in ISIAMOD is based on the principles of soil water budget, expressed as:

$$P + I_r = R_{off} + ET + IntL + D_p \pm \Delta S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.15)$$

Where I_r is irrigation depth; P is rainfall depth; ET is evapotranspiration (a combination of evaporation and transpiration); R_{off} is seasonal runoff; IntL is precipitation intercepted by the crop canopy; D_p is deep percolation depth, and ΔS is the difference between soil moisture on a daily time bases.

The water balance program of ISIAMOD starts with the quantification of the evaporative demand exerted upon the crop. The driving variables include weather, soil,

rainfall and irrigation decision input data. The weather variables induce (impose) an evaporative demand which is then translated into crop water demand by the crop. Soil water is usually held in an unsaturated state within the crop root zone for crop use. Soil moisture beyond the potential at which water can be held in the plant root zone is drained out of the zone via the process of deep percolation or deep drainage. Water is taken from the soil by the plant root to meet up with the crop water demand through the combined processes of evaporation and transpiration (evapotranspiration). When the water available within the plant root zone is insufficient to meet the crop water demand, water stress is set in which causes retardation in the crop growth process and consequently the yield. The crop growth duration is divided into four phases. These consist of establishment, vegetative, flowering and maturity growth stage. The various soil water balance modules in ISIAMOD are as follows:

(i) Potential evapotranspiration partitioning

The reference evapotranspiration (ET_o) in both SWAP and ISIAMOD models, is computed based on FAO-Penman-Monteith (Allen *et al*., 1998) by the model using the weather input data. In ISIAMOD, the ET_o is converted to crop maximum evapotranspiration (ETc) using a factor (Kc), expressed as (Stockle and Nelson, 1996):

$$ET_c = K_c * ET_o \quad \text{..... (2.16)}$$

Kc was defined as (Stockle and Nelson, 1996):

$$Kc = 1 + \left(Kc' - 1\right) * \frac{LAI}{3} \qquad if\ Kc' > 1\ and\ LAI < 3 \quad \text{..... (2.16a)}$$

$$Kc = Kc' \qquad \text{Otherwise} \quad \text{..... (2.16b)}$$

Where Kc' is peak crop coefficient, which is a crop input parameter; LAI is leaf area index with a maximum valu e of three for the reference crop (Stockle and Nelson, 1996).

The maximum evapotranspiration is partitioned to potential evaporation and potential transpiration using the fractional solar radiation interception factor. The partitions are expressed as:

$$E_p = (1 - FI) * ET_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.17)$$

$$T_p = ET_c - E_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.17a)$$

Where Ep is potential evaporation from the cropped soil surface; T_p is potential transpiration; FI is fractional solar radiation interception factor, and ET_c is the crop maximum evapotranspiration.

when the soil surface layers of a cropped field become dry and the potential soil evaporation cannot be met, sensible heat originate from between crop rows and is partially or totally transferred to the crop canopy, which increases the potential transpiration. The sensible energy (H) transfer was expressed as:

$$H = (ET_c - E_p) * St \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.18)$$

Where

$$St = 1 \; for \; LAI \geq 1.5 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.18a)$$

$$St = 0.67 * LAI \; for \; LAI < 1.5 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.18b)$$

(ii) Actual evaporation

The actual evaporation from the soil surface of a cropped area was assumed to occur in two phases. The first phase occurs when the soil is wetted by irrigation or rainfall. Evaporation occurs first at potential rate, and subsequently as a function of the soil moisture content. ISIAMod expressed the rate of evaporation as:

$$E_a = E_p \qquad if\ \theta \geq \theta_{fc} \quad \text{.....(2.19)}$$

$$E_a = E_p * \frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}} \qquad \text{Otherwise .....(2.20)}$$

The second phase of evaporation sets in when the soil moisture content of the evaporation layer reaches the wilting point. The second phase of evaporation was expressed as (Campbell and Daiz, 1988):

$$E_a = E_p * \left[\frac{\theta - \theta_{adwc}}{\theta_{pwp} - \theta_{adwc}} \right]^2 \quad \text{.....(2.21)}$$

$\theta_{adwc}$is air-dry soil moisture content, given as one-third of the soil moisture content at wilting point (Stockle and Nelson, 1996). Other parameters are as previously defined.

Where E_a is actual evaporation from the cropped soil surface; E_p is potential evaporation from the cropped surface; θ is moisture content of the soil; θ_{fc} is moisture content of the soil at field capacity, $\theta_{pwp}$is moisture content of the soil at wilting point, and θ_{adwc} is air-dry soil moisture content, given as one-third of moisture content wilting point (Stockle and Nelson, 1996

(iii) Crop actual transpiration

The actual transpiration (root water uptake) module of ISIAMod was based on Plauborg*et al.* (1996) transpiration function given as:

$$T_a = T_p \qquad if\ \theta \geq \theta_{fc} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.22a)$$

$$T_a = 0.0 \qquad if\ \theta \leq \theta_{pwp} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.22b)$$

$$T_a = T_p * \left[1 - \left(\frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}}\right)^{\frac{CT}{T_p}}\right] \qquad \text{Otherwise} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.23)$$

Where T_a is actual transpiration; T_p is potential transpiration, and CT is an empirical soil dependent constant of a range of 10 to 12 mm/day (Plauborg*et al.*, 1996). The other terms are as previously defined.

In SWAP model potential soil evaporation and crop transpiration depend on leaf area index and exponential power of extinction coefficient for global solar radiation (or the product of extinction coefficient for diffuse visible light and extinction coefficient for direct visible light). On the other hand, in ISIAMOD they depend on the changes of volumetric soil moisture between the limit of field capacity and permanent wilting point.

(iv) Surface runoff module in ISIAMOD

Surface runoff in ISIAMOD is based on curve-number techniques. It occurs when precipitation exceeds a threshold value depending on the land management system as also explained in (Schwab *et al.*, 1993):

$$RF = 0.0 \qquad if\ \Pr \leq 0.2 * S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.24)$$

$$RF = \frac{(\text{Pr} - 0.2 * S)^2}{\text{Pr} + 0.8 * S} \qquad \text{Otherwise} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.25)$$

$$S = \frac{25400}{CN} - 254 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.26)$$

Where RF is runoff (mm), Pr is precipitation (mm), and S is the surface storage (or surface retention) factor. The surface retention factor S, CN is a dimensionless curve number, which describes the runoff potential of the land cover soil-complex. Theoretically, the CN-values range from 1 to 100. Thus, if CN = 100, S =0, and RF = Pr. In ISIAMOD runoff and rainfall interception occurs only when there is rainfall.

(v) Soil water distribution within the soil layers and deep percolation estimation

In ISIAMOD, the soil profile is divided into stratified layers and each layer is divided into number of components. The infiltration and distribution of applied water to the cropped field and deep percolation in the model is based on the "tipping bucket" method by Zhang *et al.*, (2004). By this method, it means that each compartment is assumed to be filled with to "field capacity" after irrigation or rainfall before passing on any excess water to the next compartment below. In this way, any excess water beyond the bottom layer of the soil depth is term deep percolation. Upward movement of water by capillary rise is not simulated in ISIAMOD. SWAP model on the other hand simulates soil water dynamic based on the solution of Richard's equation. It also simulates flow of water in cracks and soil water repellence, while ISIAMOD assumes a well-drained soil profile.

2.4.2.2 Assumptions and limitation

The soil is a medium of interaction between the crop and water supply, and the entire soil profile is assumed to be an unsaturated medium;

i. Soil surface represent the upper boundary and freely drained bottom layer represent the lower boundary;
ii. The soil profile is divided into three zone: the soil evaporation takes place in the topmost zone which is not more than 10cm depth, and the second and third zone is where plant water for transpiration takes place;
iii. For all soil-crop combination, the soil evaporation and crop transpiration are strongly dependent on the function describing LAI;
iv. No drainage impediment, that is , high hydraulic conductivity;
v. Water application is less than or equal infiltration rate and soil water is uniformly distributed at the end of each day;
vi. Water is the only parameter affecting the crop yield, that is, no simulation of nutrient effect;
vii. No contribution from groundwater, that is, the only source of water is through irrigation or rainfall.

2.4.2.3 Initial and boundary conditions

The initial soil moisture condition before planting is taken as the initial condition of the soil. The soil surface, with crop is taken to be upper boundary and a free drainage at the bottom of the profile as lower boundary condition.

2.4.2.4 Input and output of ISIAMOD model

The input data required in the model include weather, soil, crop, and irrigation scheduling decisions. The minimum weather data required are daily maximum and minimum ambient temperatures for the duration of crop growth. The optional weather parameters are wind speed, maximum and minimum relative humidity, sunshine hour or solar radiation. The soil input data include volumetric soil moisture content at field capacity and at wilting point, initial soil moisture contents, bulk density, and the percentage of sand in the soil texture. The crop input data include maximum rooting depth, maximum leaf area index, potential (non-water limited) harvest index, radiation use efficiency (RUE), radiation extinction coefficient, and peak crop water use coefficient (Kc). Others include crop base and optimum temperatures; leaf area index shape factors; water-limited harvest index adjustment factors; crop planting, emergence, and physiological maturity dates; days from planting for the start of each of the four crop growth stages, and fraction of the crop growth duration at which leaf area index started to decline. The model divides the crop growth stages into four: crop establishment, vegetative, flowering and maturity (which include seed formation through to maturity). The soil water balance outputs of ISIAMOD are: potential and actual evapotranspiration (ET), Potential and actual soil evapotranspiration, potential and actual crop transpiration, surface run-off and deep percolation.

2.5 Models Assessments

The Performance of the models were assessed quantitatively by comparison of the models' simulated results and measured data using the following statistical indicators, as given by Mahdian and Gallichard (1995), and Panda *et a*l (2004):

Average error of Bias (AE) = $\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)$ ……. (2.24)

Coefficient of variation $(CV) = 100 * \frac{\left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5}}{O_m}$ …… (2.25)

Root Mean Square Error $(RMAE) = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5}$ …….. (2.26)

Modeling efficiency $EF = \frac{\left[\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}(P_i - O_i)^2\right]}{\sum_{i=1}^{n}(O_i - O_m)^2}$ …….. (2.27)

Coefficient of Residual Mass $(CRM) = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i}$ …… (2.28)

Where: P_i is simulated values; O_i is measured values O_m is mean of measured values, and is number of observations. The AE is a measure of bias between simulated and measured data; values close to zero indicate that the average simulated values are similar to the observed or measured values. The CV is a measure of variability while the RMSE is a measure of precision. AE and RMSE criteria are more related to precision (they decrease with increase in precision). The EF is the modeling efficiency. It gives the degree of fit

between simulated and measured data. It varies between –α, for total lack of fit, and 1 for an exact fitting. CRM is an indicator of the model to over or under predict measured values.

The numerical accepted range of values of these statistical indicators when applied to agro-hydrological models performance analysis as obtained by different authors in literatures internationally are presented in the results and discussion section of this thesis.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

The data used to run the models include: soil and crop data from the experimental field conducted, and weather data from a meteorological station. The field experiment was set-up at the experimental field of the Department of Agricultural Engineering, Ahmadu Bello University Samaru, Zaria, Nigeria. The field experiment consists of lysimeter studies of the components of soil water balance of rain-fed maize (SAMMAZ-28) cropped field. The performance evaluations of the two models were done using the field and lysimeter measured data as reference values for the comparison. Soil water balance components were estimated directly from the field and simulated using the two models. Statistical tools were used to compare the estimated results from the field with the simulated ones using the models.

3.2 Description of the Study Area

The study was carried out during the 2013 rainy season at the experimental fields of the Department of Agricultural Engineering, Ahmadu Bello University, Zaria, Nigeria. Zaria lies on latitude $11^{o}11'$N, longitude$7^{o}38'$E and altitude 686m above mean sea level. It is located within the Northern Guinea Savannah ecological zone of Nigeria. The climate of the area can be describe as semi-arid, with three distinct seasons: the hot dry season from March to May; the warm rainy season, June to early October, and the cool dry season, which spans from late October to February. Table 3.1, shows the summary of the average monthly weather data during the experiment.

Table 3.1: Shows the summary of the average monthly weather data during the experiment.

Months	T_{max} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	Wind speed (m/s)	R_n (MJ/m^2)	Sun-shine hr. (hr)	P* (mm/ day)	E_p** (mm/ day)
July	30.6	22	80.0	67.6	1.8	22.2	5.3	10.2	4.7
Aug.	29.6	23	83.5	72.7	1.7	17.7	4.5	5.3	4.5
Sept.	31.4	22	77.3	65.6	1.2	20.4	6.2	7.8	4.6
Oct.	32.8	21	60.0	48.4	1.1	21.6	7.3	0.5	5.0

P* is the precipitation
E_p is the pan evaporation
R_n* is net radiation

The soils of the study area are predominantly heavy clay soils which crack when dry. The surfaces are covered with grasses, most of which survived the dry season. The soil has high proportion of organic matter, fine sand at or near the surface. Studies by Klinberg and Higgins (1963) and Awujoola (1979) have shown that the soil at Samaru-Zaria is Alfisols. The soil physical properties of the experimental site are given in Table 3.2.

Table 3.2: Soil physical properties of the Experimental Field

Soil Depth (cm)	Hydraulic Conductivity (cm/sec.)	Bulk Density (g/cm^3)	Moisture @ FC[a] (g/g)	Moisture @ PWP[b] (g/g)	Particle Size Distribution (%)			
					clay	silt	sand	Textural Class
0-10	0.01	1.39	0.175	0.070	24	20	56	Sandy clay loam
10-30	0.08	1.30	0.173	0.077	20	20	60	Sandy loam
30-45	0.04	1.37	0.194	0.094	22	18	60	Sandy clay loam
45-60	1.70	1.34	0.197	0.115	24	20	56	Sandy clay loam
60-80	2.31	1.40	0.226	0.149	26	14	60	Sandy clay loam

a is the field capacity (@ 0.33bar.

b is the permanent wilting point (@ 1.5bar)

3.3 Treatments and Experimental Design

A field of size 0.053ha was prepared into ridges of 75cm apart and planted with a maize crop (Sammaz-28). Nine set of mini-Lysimeter planted with the same crop were installed in an excavated pit in the middle of the experimental field. The nine lysimeters comprises of three treatments, replicated three times. The treatments consisted of no-crop lysimeter setup to monitor evaporation (E); a cropped and mulch lysimeter covered with black polythene as mulch material to monitor crop transpiration (T); and a no-mulch cropped lysimeter to monitor evapotranspiration (ET).The nine weighing-type mini-lysimeters were arranged in a completely randomized complete block design.

3.4.1 Description of the mini-lysimeter

Each lysimeter consists of a plastic tank container which is of 47.5cmdiameter and 85cm deep, the weighing system, the runoff system, the drainage system and a platform to which the lysimeter tank was resting. Plate 3.1 shows the layout of the experimental set-up.



Plate 3.1: Typical Set-up of the Mini-Lysimeter

The weighing system consists of a vehicular tube of size 155/156-13 filled with water and connected to a manometer glass tube of size 1.5m long by means of a rubber hose. The manometer glass tube was attached to a graduated vertical wooden pole. This arrangement was made so that the water in the vehicular tube can rise to a height in the manometer glass tube depending on the pressure exerted on it by the weight of the lysimeter tank. The tube was placed on a platform and a ply-wood was used on top of the tube to concentrate the weight of lysimeter tank squarely on it. The platform consist of a metal frame to give the

whole system a good footing and wooden flat-top with an opening in the center for conducting excess water (drainage water) from the lysimeter tank to the drainage system. The weighing system is to help note any change in weight of the lysimeter tank due to inflow and outflow of water from it and indicate that by displacement of water in the manometer glass tube on the graduated vertical pole.

The drainage system of the lysimeter consisted of a plastic bowl of 27cm diameter and 20cm deep placed to collect the drainage water through some perforation made at the bottom of the lysimeter tank. The perforation made allows the excess water in the lysimeter soil to drain easily. The drainage collector was fitted such that the collector was suspended above the ground surface to prevent rainwater or runoff from surrounding from entering into it.

The runoff system consisted of a plastic bucket of 28cm in diameter and 34cm deep connected to the top of the lysimeter tank using a rubber hose. The hose rubber collects the runoff water from the lysimeter surface soil through the outlet edge and channeled it to the plastic bucket serving as the runoff collector. The collector was placed at a lower elevation compared to the lysimeter tank so that the runoff water from it flows by gravity to the collector. The runoff collector was then covered with a lid to prevent direct rainwater from entering into it.

Soil dug out from the experimental field was placed in each of the lysimeters as close to *in situ* condition as possible: - A fine wire mesh was first used on the perforated drainage hole at the bottom of the lysimeter tank, followed by gravel on top of the wire mesh to aid drainage of the excess water from the lysimeter's tank and to prevent soil particles from

blocking the perforation. The soils dug out from the experimental field were repacked into the lysimeters in layers as the field's soil stratification exists. The lysimeter tank repacked with the soil was first left under rainfall to allow the soil to settle naturally and then more soil added to the tank. Good footing for the platform of the lysimeter was provided by pouring gravel and a concrete slab at the base of each lysimeter stand. This is to keep each lysimeter upright and to prevent it from sinking due to the weight of the lysimeter. A drainage path (trench) was made to connect all the lysimeter's piths and to allow flow of water out of pith and runoff water from the field.

3.4.2 Calibration and field set-up of the lysimeters

The lysimeters were first calibrated in the laboratory to establish a relationship between the weights of the lysimeter tank and the height of water in the manometer glass tube before taken to the field for installation. The calibration was carried out by loading and unloading of some known weight into the lysimeter tank while noting the height of water in the manometer glass tube at each level of loading. These heights were recorded both during loading and unloading of the weight to note the presence of hysteresis in the relationship between the height of rise of the water column in the manometer and the change in weight of the lysimeter tank. The relationship between the lysimeter weight and the height of water in the manometer tube was established as:

$$W = 1135.8H + 202.5 \quad \text{..... (3.1)}$$

$$R^2 = 0.996$$

Where: W is the weight of the Lysimeter in gramme (g) and H is the height of water in the manometer glass tube in cm.The difference in weight of the Lysimeter tank obtained

between two consecutive days is translated to depth of water (W_h) in mm/day by multiplying eqn. 3.1 with a factor "CF=0.00757" (Appendix C), which result to:

$$W_h = 8.6H + 1.5 \quad \text{..... (3.1a)}$$

This factor was based on the surface area of the Lysimeter and the density of water as explained in appendix C. Note: equation 3.1a shows that when H=0, W_h=1.5 cm. Since we are interested on the change per day (W_{1+I} - W_i), this would cancel out.

Other soil water balance components such as deep drainages and runoffs are measured directly from each of the lysimeter. The expressions used for the computation of the daily evaporation, evapotranspiration and transpiration from Lysimeter are as presented in Equation 3.2:

$$E, T, ET = P_i - R_{offi} - D_{pi} - [(W_{I+1} - W_i)*CF] \quad \text{..... (3.2)}$$

Where: P_i = rainfall amount (mm) of day ''i'' ; R_{offi} = runoff of day ''i'' ; D_{pi} = deep percolation (mm) of day ''i'' ; W_i = weight of lysimeter soil (g) on day ''i'' ; W_{i+1} = weight of lysimeter soil (g) on the next day interval; CF = conversion factor of the lysimeter (appendix C); E, T, and ET; is the evaporation (from bare soil), transpiration (from cropped soil covered with black polythene) and evapotranspiration respectively.

3.5 Calibration and Field Set-up of Gypsum Blocks

A total of ten soil moisture resistance blocks (gypsum blocks) were installed within the potential root zone depth in the field along the crop's rows. The depths of installations were5, 20, 37.5, 52.5 and 70cm, within the potential root zone depth to measure soil moisture at 0-10, 10-30, 30-45, 45-60 and 60-80cm depths, respectively.This was replicated two times making a total of ten gypsum blocks. The blocks were first soaked in

clean water for 24hrs before their installation to expel air bubbles within the blocks. After digging each of the various holes in the ground at the stated depths above using a hand auger to installed the blocks, soil and water slurry of creamy consistency was made and a half-handful of it was placed in each of the hole before pushing the blocks to the bottom of each hole. This forces the soil water slurry to envelop the blocks and thereby preventing soil void around the blocks. The holes were then back-filled and tamp in small increment. The lead of each block was then fasten to a stake and tagged using a number in accordance to the depth of the blocks so that they can be kept clean and are easily located for reading. The gypsum blocks were locally fabricated and calibrated on the field to relate electrical resistance of the soil to the gravimetric moisture content of the soil of the experimental field using the method of Ejieji and Fasasi (2003). The calibration curve was defined by powered function obtained as:

$GMC= 87.7M^{-0.426}$…………………….…………………..……….. (3.3)

($r^2 = 0.9713$);

Where GMC is gravimetric soil moisture content (%), and M is meter reading which can be converted to soil moisture resistant in ohms (Ω) using the meter’s manual.

3.6 Rain-gauge Installation

Two non-recording rain-gauges were installed on the field to measure the depths of rainfall amount. They were located on strategic locations to collect the rainfall directly without interception of the rainfall by the growing crops.

3.7 Agronomic Practice

A systemic herbicide (glysophate) was first applied to the field before the land preparation to clear the weeds in the field. The field and the lysimeters were planted with maize on 17th July, 2013. Pre-emergence herbicide was applied two days after planting to take care of weeds that might still remain active. Weeding was carried out twice on the field and lysimeter before each fertilizer applications (i.e. basal dose and top dressing applications). Compound fertilizer (N.P.K. 15:15:15)was applied at the rate of 60KgN/ha as basal dose at two weeks after germination and urea (N.P.K. 46:0:0) fertilizer was applied at 60KgN/ha rate and at five weeks after germination as top dressing application to bring the quantity of nitrogen applied to 120KgN/ha. This is as recommended by the Institute for Agricultural Research (I.A.R), Samaru, Zaria for maize crop in the study area. Earthing of the maize was followed after the second fertilizer application to give the maize good footing to the ground.

The crops were grown under rainfall condition. However, during the latter part of the growing season, the crops on the lysimeters were noticed to show some signs of wilting due to moisture stress. This was due to longer interval of days between successive rainfalls. As such the lysimeters were irrigated with known depth of water. Details of the irrigations depths and rainfall events are presented in Appendix B. These signs of stress were however not noticed on the crops in the field surrounding the lysimeters. This was because the crop on the lysimeter is on a smaller volume of soil compared to that of the field. The growth of both maize crop in the lysimeter and field were satisfactory. The field and the lysimeters crop were given the same agronomic attention. Plates 3.2, 3.3, and 3.4 show the lysimeters in the fields at different crop growth stages.



Plate 3.2: Field and Lysimeters set-up at crop establishment growth stage



Plate 3.2: Field and Lysimeters set-up at early vegetative crop growth stage



Plate 3.4: Field and Lysimeters set-up at crop maturity growth stage

3.8 Data Collection

Experimental data were collected from the rain-gauge, crop, gypsum blocks, and lysimeters: Rainfall data from the rain-gauge; leaf area index (LAI), crop height and crop rooting depths from the crops; soil moisture changes from the gypsum blocks; and processes of evaporation, transpiration and evapotranspiration from the lysimeters. These data were used for the estimation of soil water balance components from the field, lysimeter and for the models simulations.

3.8.1 Field soil moisture measurement from gypsum blocks

The soil moisture status of the field was monitored daily throughout the crop growing season using soil moisture resistance blocks. The soil electrical resistance measurements were carried out daily using Delhorst moisture tester (Model KS-D1) throughout the crop

growing season. The meter readings were converted to gravimetric moisture content (% dry weight basis) using equation 3.3 above.

Monitoring of soil moisture starts after two week of rainfall for the gypsum blocks to get established in the soil.

3.8.2 Determination of crop parameters

Crop parameters such as plant height, leaf area index and plant rooting depth were determined on weekly basis. Plant heights and leaf areas were conducted on each of the plant on the lysimeter and some sample on the field. Plastic tape was used to determine plant's height and the leaf area was determined using the equation proposed by Dwyer and Stewart, (1986) as:

$$\text{Leaf Area, LA} = [L*W*A] \quad \ldots\ldots (3.4)$$

Where;

LA is leaf area, L is leaf length, W is maximum leaf width and A is a constant (A=0.75).

The leaf area index (LAI) of the maize was the determine using the relationship in Equation 3.5;

$$\text{LAI} = \frac{[L*W*A]}{(crop\ spacing\ )*(intra-row\ spacing\ )} \quad \ldots\ldots (3.5)$$

To calculate the leaf area index (LAI) in the field, sample of the maize plant was first marked out. On each plant stand, the number of leaves on each plant was counted, and length and maximum width of each leave was also measured using a tape. The total sum of the area

($[L * W * A]$) of the leaves on each plant stand was then divided by the ground area ($(crop\ spacing) * (intra - row\ spacing)$ of the maize stand. This was done for all the plant in the sample taken and the average was then obtained.The rooting depths from crop establishment to vegetative stage were determined weekly by destructive means (i.e., by opening a trench around some selected crops on the field and washing away the soil to expose the total root system for measurement). From the vegetative stage of the crop's growth, rooting depths of the crops were determined at their maturity stage, and a linear relationship was assumed (Campbell and Daiz, 1988).

3.8.3 Data from the lysimeter

Water leaves the lysimeter tank through the process of evaporation and transpiration on daily basis, and that was reflected on the lysimeter weighing system by changing of water levels in the manometer glass tube. Therefore, measurement of the daily process of evaporation, transpiration and hence evapotranspiration was based on the changes of water level in the manometer glass tube. The difference in the level of water in the manometer glass tube between two consecutive day was as result of either water added, crop water use, water drained from the bottom of the lysimeter runoff, or a combination of two or more of the listed variables. When there is no rainfall, the difference in weight of the lysimeter would be due to evapotranspiration, transpiration and, or evaporation depending on the lysimeter treatment. The daily depths of runoff drainage water were estimated from the water collected in the runoff and drainage collectors respectively when there is rainfall. These daily components of soil water balance (that is, depths of evaporation, transpiration, evapotranspiration, runoff and drainage water) from the lysimetres were determined using equation 3.2.

3.8.4 Determination of field actual crop evapotranspiration (ET_a)

The actual crop evapotranspiration (ET_a) was calculated from the measured soil moisture content data from the field using the soil moisture depletion method as outlined by Michael (1999). The actual daily average evaporation (AET), which is same as $ET_a$was expressed as:

$$AET = \sum_{i=1}^{n} \frac{(VMC_{1i} - VMC_{2i})D_i}{t} \qquad \text{.....(3.6)}$$

Where

AET is average daily AET between successive soil moisture content sampling period (mm/day); VMC_{1i} is volumetric soil moisture content (m^3/m^3) at the time of first sampling in the i^{th} soil layer; VMC_{2i} is volumetric soil moisture content (m^3/m^3) at the time of second sampling in the i^{th} soil layer; D_I is depth of i^{th} layer; n is the number of soil layers sampled in the root zone depth D, and 't' is the number of days between successive soil moisture content sampling.

3.8.5 Estimation of reference evapotranspiration (ET_o)

For the calculation of daily reference evapotranspiration (ET_o), the FAO Penman-Monteith combination equation (Allen et al., 1998) was applied using the weather data obtained from the Institute for Agricultural Research (IAR) meteorological station close to the research area, Samaru. The combination equation is the preferred and reliable method for determining reference evapotranspiration worldwide (Inman-Barber and McGlinchey 2003). The ET_o was estimated using equation 2.7 above. The formulae used for calculation of

various parameters of equation 2.7 are presented in appendix C. Soil heat flux (G) was ignored beneath the hypothetical crop surface for day-time scale (Maruyama et al. 2004), since soil heat flux at the magnitude of the day below the grass reference surface is relatively small. Kc was calculated using the relation of AET/ET_o(Watanabe et al. 2004), where AET (ET_c, as in equation 3.6) was the measured actual evapotranspiration (mm/d) and $ET_o$was the FAO reference crop evapotranspiration (mm/d).

$ET_c = K_c * ET_o$ …… (3.7)

3.9 Model Simulation

SWAP Model Input Data Files

The input data for SWAP model where weather, rainfall and or irrigation soil, crop and model's constant.

a. Weather input data

The simulation was conducted from July 15 to October 18, 2013 for the crop growing season. Weather variables used in SWAP were solar radiation, minimum and maximum temperature, wind speed, actual vapour pressure and rainfall. These weather data were obtained from the field, station from the Institute of Agricultural Research (I.A.R), which close to the experimental site to run the model. Penman-Monteith equation was used for estimation of evapotranspiration. The detail weather input file presented in Appendix A.

b. Crop input data

Crop height, leaf area index and plant's rooting were estimated at the experimental site as outline in section 3.6.2. Plastic tape was used to determine plant's height and the leaf area was determined using the equation proposed by Dwyer and Stewart, (1986) in eqn. 3.6. The other crop input parameters are crop constants. The default values where used in the SWAP program, and adjustments in some cases within acceptable values of some constants were made. The detail of the crop input values are presented in Appendix A.

c. Soil input data

SWAP 207d, allows the use of a soil hydraulic database parameters based on the field soil texture. The soil input data include number of layers and compartments, soil hydraulic function, soil texture, rooting depth limitation. The soil water content, soil water retention and soil hydraulic conductivity were related on the basis of Mualem's theory (1976), and are based on Van Genuchten parameters (K_s, Θ_s, Θ_r, α, n and l). The detail of the soil input file is given in appendix A.

d. Initial and boundary condition

In SWAP, soil surface with crop was taken to be the upper boundary condition and for the lower boundary condition, a Lysimeter with free-drained bottom was chosen among the options outline in section 2.3.1.4 of this work.

ISIAMOD Input files

ISIAMOD used as inputs, data from weather, rainfall and or irrigation, soil, and crop. The files of weather, rainfall, irrigation, soil and crop were prepared as text file and used to run the model.

1. Weather input file

Among the eight available options of weather parameter combination given by ISIAMOD, the third option was used in this research. In this option, the weather combinations are maximum and minimum temperature, wind speed, maximum and minimum relative humidity and sunshine hours.

2. Crop input file

The crop input data was entered in the following order as text-file:

I. Planting date, month and year;

II. Seed emergence date, month and year;

III. Maturity date, month and year;

IV. Maximum rooting depth, maximum leaf area index, radiation use efficiency (RUE) for the vegetative and flowering growth stages, RUE for the grain filling growth stage, harvest index (non- water stress), peak crop coefficient, and radiation extinction factor;

V. Base temperature, optimum temperature, and fraction of growth duration at which leaf area index decline starts, leaf area index parameter ‘a’, leaf area index parameter ‘b’, leaf area index decline adjustment factor, harvest index adjustment factor for the flowering growth stage, harvest index adjustment factor for the grain filling growth stage;

VI. Day after planting at which establishment growth stage starts (Zero);

VII. Day after planting at which vegetative growth stage starts;

VIII. Day after planting at which flowering growth stage starts;

IX. Day after planting at which grain filling growth stage starts;

3. Soil data file

The soil input data was entered in the following order as text-file. Each group of data was entered into a single line-filled separated by comma.

- Number of soil profile layer, curve number, bare soil evaporation coefficient, soil-transpiration coefficient;

- Serial number of soil layer, thickness of soil layer (m), number of compartments the profile layer is to be divided, volumetric soil moisture content at field capacity (m^3/m^3), volumetric moisture content at wilting point (m^3/m^3), volumetric moisture content at planting (m^3/m^3), dry bulk density, wet bulk density, percent sand. The same order of entering should be followed to enter the other data for each profile layer, using one line-field for a profile layer.

4. Irrigation input data file

The data was to be entered in the following order:

- Total number of irrigation events for the season;
- Date, month, year, and depth of water to be applied. One line-filled was to be used for each date of irrigation.

5. Rainfall input data file

The rainfall input data was entered in the following order:

- Total number of rainfall event during the crop growing season.
- Date, month, year, and depth of water to be applied. One line-filled was to be used for each date of rainfall.

6. Initial and boundary condition

The soil water in ISIAMOD was initialized according to the initial soil moisture condition before planting (that is, the initial boundary condition used). The soil water balance computation in ISIAMOD assumes a well-drained soil.

3.10 Model Simulation Run

In SWAP model, after the input files have been prepared from the graphical interphase of the model, the files are run on a DOS environment as a 'batch file'. For the ISIAMOD on the hand, after preparing the input file as text files using 'note pad', the files are run on a 'command prompt' environment. All the inputs and output data of the two models are presented in Appendix A and B, respectively.

3.11 Model Evaluation

The Performance of the models was assessed by graphical and statistical means. Graphical comparison of measured and simulated daily soil water balance components data was made. Quantitative comparisons of the simulated and measured data were also carried out using equation 2.24 through 2.28.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the field observed and simulated soil water balance components. The components of soil water balance considered and measured during the field experimentation were; daily evapotranspiration (ET), transpiration (T), and daily evaporation ($E_{crop.}$) from cropped field[obtained through separation of transpiration from evapotranspiration processes (ET-T)], evaporation from bared soil (E), surface runoff and deep percolation from lysimeters set-ups installed in the field. The results of these same soil water balance components as simulated using the two models were also presented.

4.2 Field Soil Water Balance

4.2.1 Daily rainfall, deep percolation and runoff depths

Figure 4.1, 4.2 and 4.3 show the daily trend of the depth of rainfall, drainage and runoff from no-mulch crop lysimeter set-ups, with mulch materials, and for no-crop lysimeter set-ups.

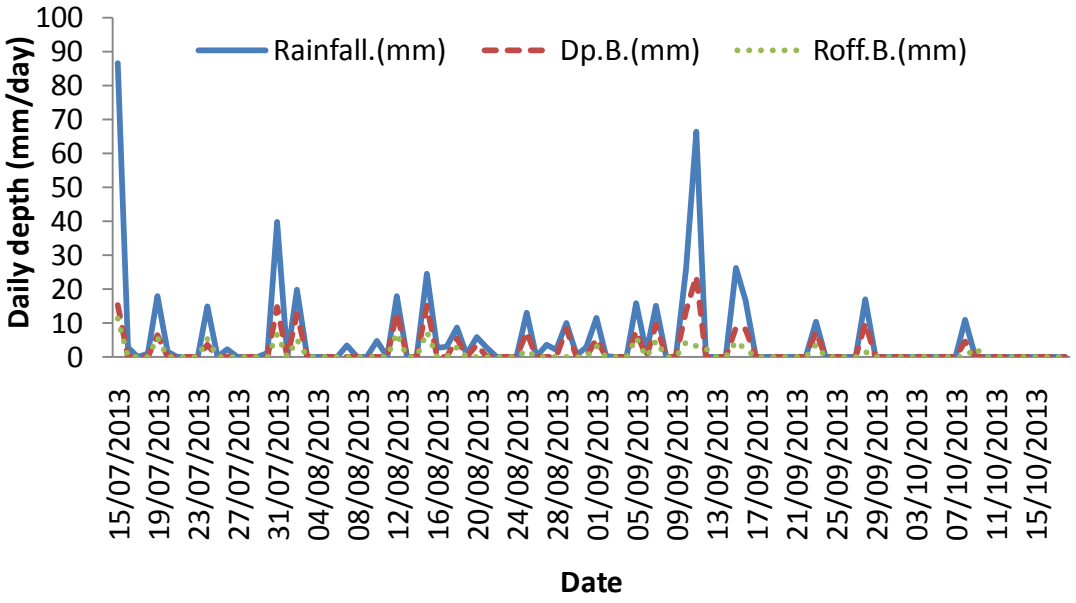


Figure 4.1: Rainfall, Drainage and Runoff from cropped lysimeter without mulch material

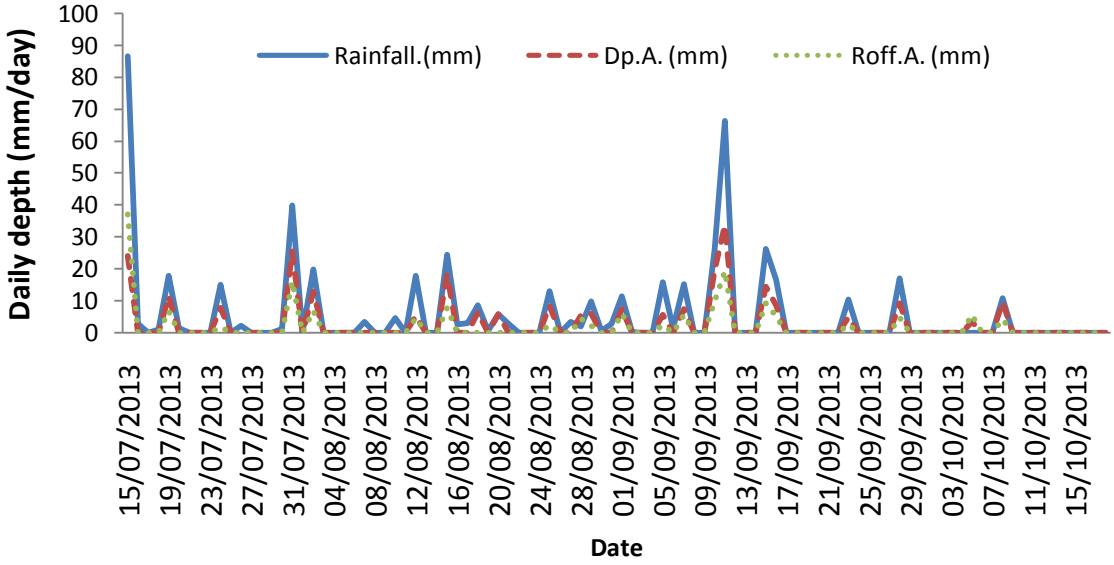


Figure 4.2: Rainfall, Drainage and Runoff from cropped lysimeter with mulch material

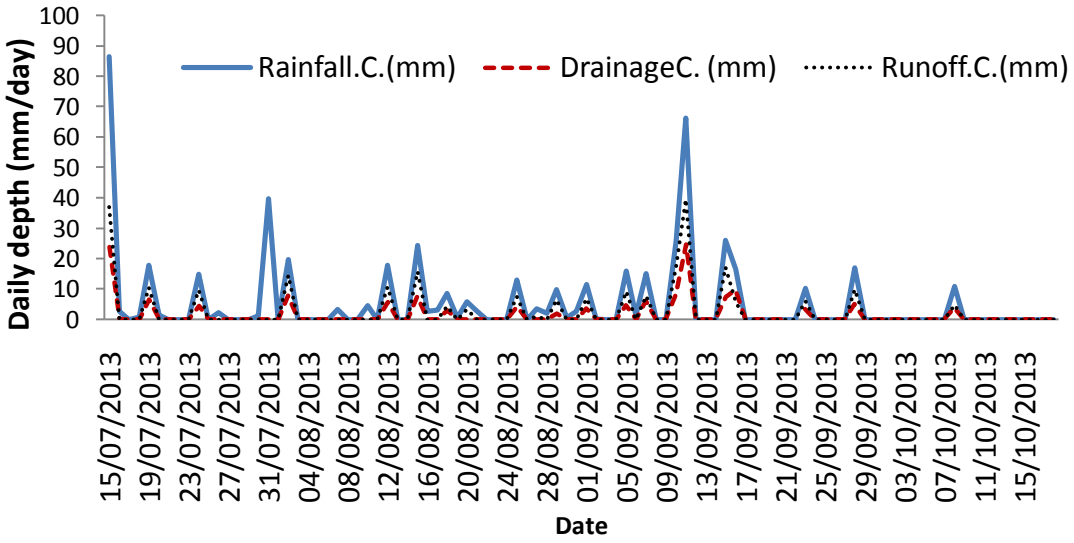


Figure 4.3: Rainfall, runoff and drainage from uncroppedLysimeter set-up

The depths of the rainfall varied from 0.7 to 66.3mm. The peak rainfalls occured in the sub-period of31 July and 11 September, 2013 with rainfall amounts of 39.8 and 66.3 mm, respectively. The total rainfall events recorded were 37 during the field experimentation. Table 4.1 presents the monthly amount of rainfall depths for the crop growing. The seasonal rainfall depth during the field study was 511.5mm. The total irrigation depth supplemented to each of the lysimeters was 205 mm, making a total of water inflow to the system to be 716.5 mm.

Table 4.1: Monthly amount of rainfall depths recorded during the crop growing period

Month	monthly Rainfall (mm)
July	167.7
August	126.2
September	206.7
October	10.9
Total	511.5

The daily drainage from the no-mulch cropped lysimeter ranged from 1.9 to 43.8 mm while that from the mulch cropped lysimeter vary from 2.2 to 40.8 mm, and that of the no-croplysimeter drainage varied from 1.1 mm to 24.8 mm. On the other hand, the runoff depths from the no-mulch cropped lysimeter ranged from 0.18to 20.2mm and that from the mulch cropped lysimeter vary from 0.1to 22.6mm, while no-crop lysimeter runoff ranged from 2.0mm to 39.6mm.

The seasonal drainage from no-mulch cropped lysimeter and with mulch material is200.1 mm and 173.9 mmrespectively, while that from no-crop set-up is 142.7 mm. On the other hand, runoffs were: 88.6mm and 90 mm, for no-mulch cropped lysimeter and that with mulch material respectively, while the seasonal runoff from no-crop lysimter was 179.7 mm. The seasonal drainage and runoff water from the lysimeters ranges from 19.9-27.9% and 12.4-25.1%, respectively of the total inflow water (rainfall and irrigation). During the application of irrigation water to the lysimeters, the process of run-off was impeded to concentrates the water down the soil profile. So, when the irrigation water was excluded, the seasonal drainage and runoff ranges from 21.9-26% and 11.3-22.2%, respectively of the total rainfall. In all the lysimeter set-ups, except for the no-crop lysimeter, the depth of drainage water is higher than that of runoff water. The high depths of water loss through drainage process shows that drainage water should not be disregarded in the study of water balance components of any soil (with or without crop). Rafael, *et al.* (2011), obtained similar results working with drainage lysimeter in southern Brazilian Atlantic Forest region, in which their drainage water was 27.5% of the total rainfall. Igbadun (2012) also obtained similar results when estimating crop water use of rain-fed maize in samaru Zaria, Kaduna State, Nigeria. In his study, he obtained 22% and 25% as percentages of seasonal run-off and drainage,

respectively. The drainage fluxes are considered the most difficult soil water balance's components to determine especially under field plot study and are not taken into consideration in many of such studies. Stone *et al.,* (1973); Vachaud*et al.,* (1985) and Reichardt*et al.,* (1979), as cited in Rafael *et al.,* (2011) declare that the drainage is water balance component cannot be disregarded because it may represent 30% or more of the total value especially when performed in tropical weather regions. The difference between the run-off and drainage could also be attributed to the rainfall function of the study area in the period between July through August and September. These are periods that normally experience rainfall of low intensity but high duration. This can also contribute to high drainage and low runoff water experienced. This is because, a greater intensity produces more surface runoff, while a less intense and well-distributed rainfall has a greater capacity of infiltrating into the soil and consequently producing high drainage water.

4.2.2 Evapotranspiration (ET) and transpiration (T)

Figure 4.4 and 4.5 show the trend of evapotranspiration and transpiration from cropped lysimeter respectively, during the crop growing season. Table 4.1 shows the total ET and T at every growth stage.

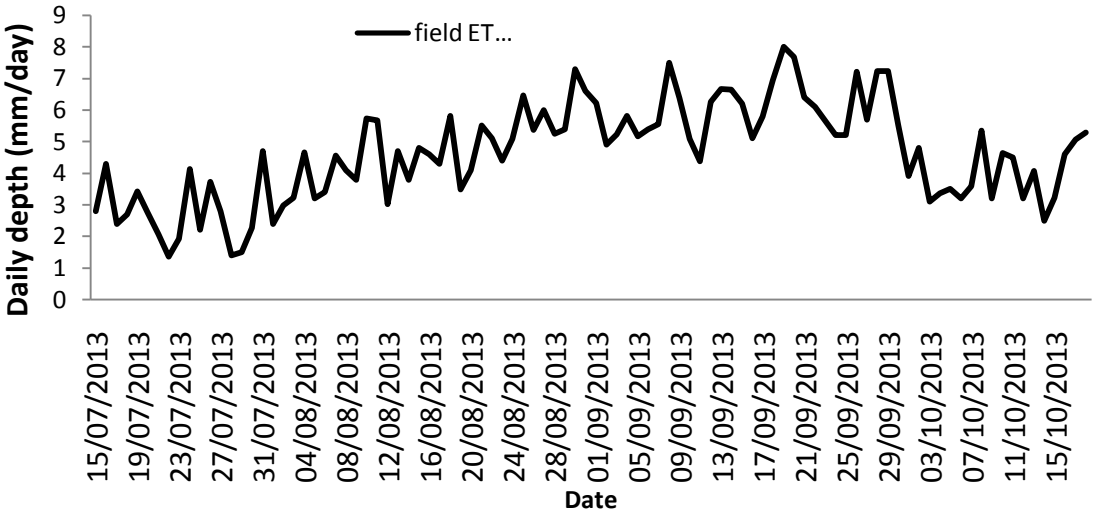


Figure 4.4: Evapotranspiration (ET) measured from the Lysimeter

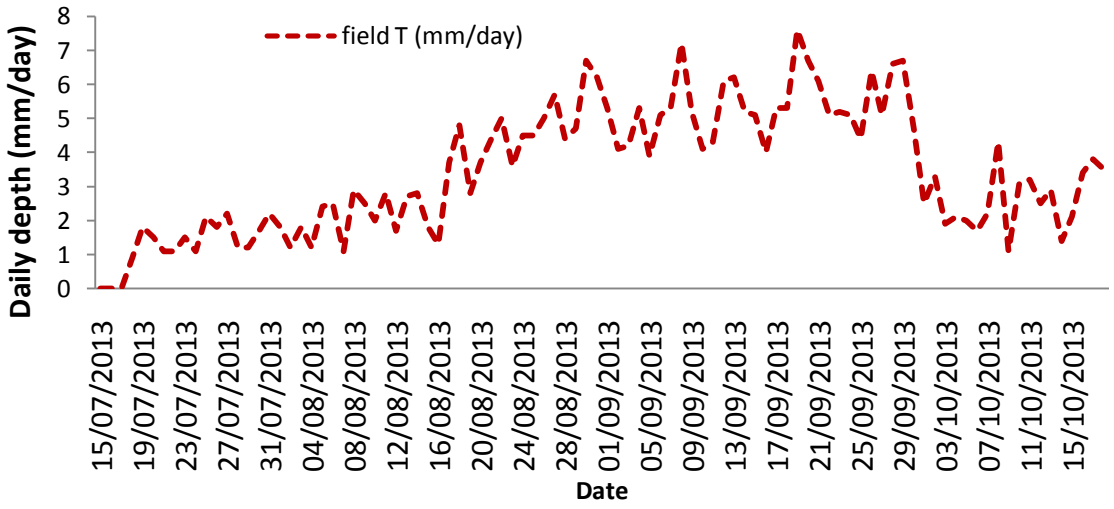


Figure 4.5: Transpiration (T) measured from the Lysimeter

Table 4.2: Shows the total ET and T with respect to the crop growth stages

Growth stages	ET (mm)	T (mm)
Establishment (0-17 days after planting)	46.5	21.4
Vegetative (18-40 days after planting)	97.4	60.5
Flowering (41-62 days after planting)	128.0	113.2
grain filling and maturity (63-84 days)	122.9	108.9
Total	395.6	304

The daily evapotranspiration varies from 1.3 to 8.3 mm/day with a seasonal average of 4.7mm/day. The daily transpiration on the other hand, varies from 0 to 7.5mm/day with a seasonal average of 3.9mm/day. Despite the slight rising and falling of the daily evapotranspiration and transpiration trends, the patterns with respect to the crop age increases from establishment stage to the vegetative stage and having its maximum at flowering to grain filling stage, from which it drops gradually to the maturity stage. The slight rising and falling is because of the changing nature of sunny and cloudy days during rainy season. However, ET and T patterns with crop age were better observed with respect to the crop age. Table 4.2 shows the total ET and T with respect to the crop growth stages. Igbadun (2012a) obtained a similar result of evapotranspiration (but call it crop water use) on the same area of study using similar mini-lysimeter, but of smaller sizes of lysimeter tank of

40 cm deep and 50 cm diameter when estimating crop water use of rain-fed maize in samaru Zaria, Kaduna State, Nigeria. Estimation of evapotranspiration of rain-fed maize crop by Aworidhe, (2011), but using micro-lysimeter also gave a similar range of results.

4.2.3 Evaporation from cropped (E_{crop}) and uncropped surface (E)

Figure 4.6 presents the trend of evaporation from cropped and no-crop lysimeter respectively. Table 4.2 shows the weekly depths of evaporative water from the cropped and uncroppedlysimeter. The evaporation from cropped surface here was estimated by separating the process of transpiration from evapotranspiration.

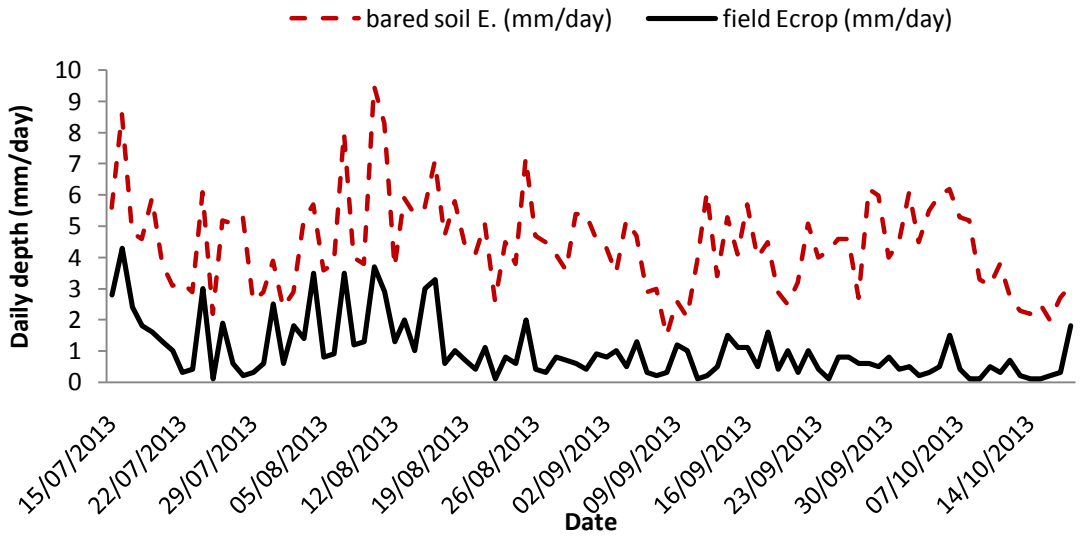


Figure 4.6: daily trends of evaporation from cropped and no-crop lysimeter set-ups

Evaporation from cropped lysimeter ranges from 4.3 mm/day at the beginning of the season to 0.2 mm/day at the maturity stage, with an average of 1.1 mm/day. During the initial growth stage period of the crop when the leaf area is small, the processes of evaporation pre-

dominate transpiration. As the crop develops and the leaves cover the soil surface, evaporation process becomes less and transpiration gradually becomes the major process. This gives the reason why the evaporation from cropped surface decreases with crop age. The evaporation from no-crop surface on the other hand, varies from 1.1mm/day to 5.9mm/day with a mean average of 3.4mm/day. The depth of water loss through this evaporation process depends on water availability in the soil. There will be more water at the soil surface of the no-crop lysimeter available for evaporation than the cropped lysimeter. As for the other lysimeters, the crops take in the water and release it via transpiration process. Table 4.2 presents the weekly depths of evaporative water from the cropped and no-crop lysimeter. The weekly trend of cropped evaporation decreases with crop age, while that of soil evaporation varies moisture availabilities from rainfall and atmospheric demand (e.g. temperature, wind and solar radiation).

Table 4.3: Weekly depths of evaporative water from the cropped and uncroppedlysimeter

Days after planting (DAP)	E(uncropped soil) mm/week	E (cropped field) mm/week
1-7	21.2	15.2
8-14	23.5	6.5
15-21	14.9	10.7
22-27	26.7	14.3
28-34	26	12.2
35-42	26	5.7
43-49	28.2	4.1
50-56	20.7	4.4
57-63	21.9	5.6
64-70	22	5.9
71-77	28.5	3.8
78-84	32.6	6.3
Total	292.2 mm	94.7mm

4.2.4 Reference (ET_o) and actual (ET_c.) evapotranspiration

Table 4.4 presents the weekly estimated reference and actual evapotranspiration from lysimeter and gypsum block.

Table 4.4: Weekly estimated evapotranspiration and potential evapotranspiration

D.A.P	ET_{c1}. (mm/week)	ET_{c2}. (mm/week)	ET_o(mm/week)	K_c
	lysimeter	gypsum block		
7-14	16.6	15.3	40.6	0.39
15-21	20.4	19.3	44.3	0.45
22-27	33.1	31.4	39.0	0.83
28-34	31.5	29.9	32.5	0.94
35-42	36.0	34.8	38.8	0.91
43-49	45.7	43.9	44.9	1.00
50-56	47.8	46.3	37.5	1.25
57-63	40.3	40.2	45.0	0.89
64-70	46.6	42.3	50.2	0.89
71-77	43.3	44.8	44.9	0.98
78-84	25.5	24.7	52.1	0.45
Total	386.8	372.9	476.4	

Table 4.4 shows; the weekly actual evapotranspiration estimated from min-lysimeter (ET_{c1}) and from field using gypsum blocks (ET_{c2}), and reference evapotranspiration (ET_o) estimated from weather data using the Penman-Monteith equation. The ET_{c1} from lysimeter compared closely with ET_{c2} from gypsum block with mean difference of 1.26 mm/week. The mean difference at a level of a 0.05 level of significance was statistically insignificant. This implies that the mini-lysimeter effectively estimated the actual evapotranspiration and so the gypsum blocks.

4.3 Comparison of models simulated and field-measured evapotranspiration

Figure 4.7 presents the daily field-measured and models-simulated evapotranspiration by the two models (SWAP and ISIAMOD) under study. Table 4.5 shows the statistical indices of the comparison between the measured and simulated data.

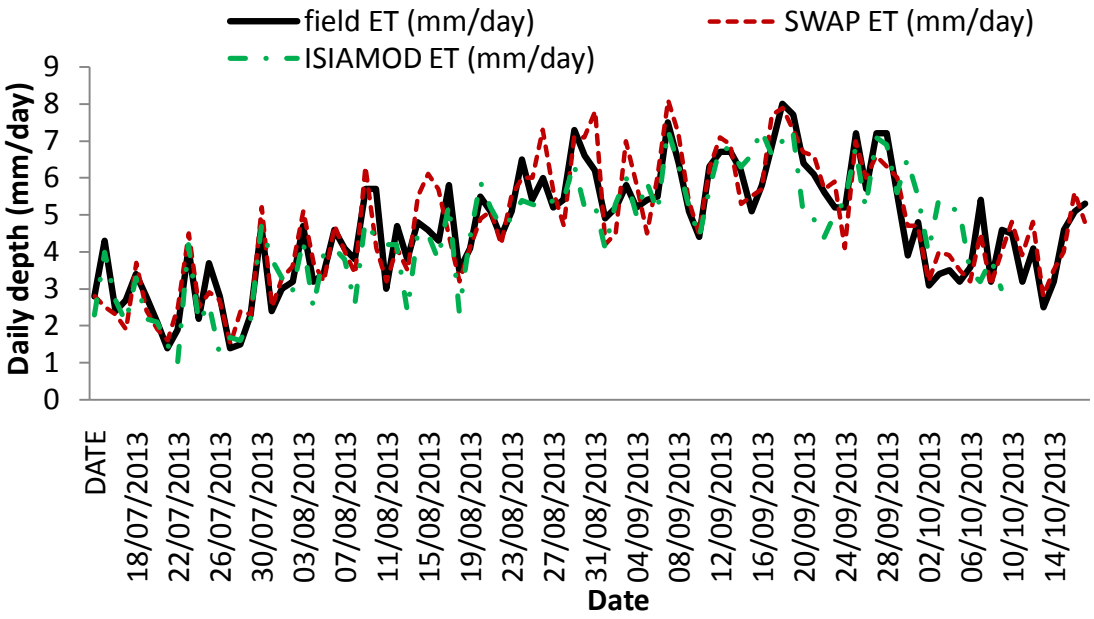


Figure 4.7: Daily evapotranspiration measured and simulated by SWAP and ISIAMOD

Table 4.5: Statistics of the comparison between simulated and measured evapotranspiration (ET)

Statistical performance indices	SWAP model evapotranspiration (ET)	ISIAMOD model evapotranspiration (ET)
AE	-0.096	-0.114
RMSE	0.62	0.31
CV (%)	8.3	11.8
EF	0.84	0.88
CRM	-0.020	0.025

For the first 20 days after sowing, the simulation of evapotranspiration (ET) by the two models and that of the field measured values are closely related. When the crops grown from the vegetative stage to when it reaches its maximum leaf area index (LAI), SWAP model over-estimated the ET. ISIAMOD on the other hand, simulated the ET optimally well except for the later part of the crop maturity stage (30/09 to 06/10/2013) where its over-estimates the ET. Generally, the two models simulated the process of ET well as evidenced by the statistical analysis.

The CRM shows that SWAP model has a tendency to over-predicts the ET by 2%, while ISIAMOD under-predicts the model by 2.5%. The modeling efficiency (EF) is 84% for SWAP and 88% for ISIAMOD. These values (of EF) show a close relationship between the measured and simulated data and hence the prediction capacity of both models is good. Igbadun (2012b) used ISIAOMD to simulate the ET of an irrigated maize crop in Tanzania

during 2004 and 2005 season and obtained the modelling efficiency (EF) to range from 0.56 to 0.95 with CRM of -0.01 to -0.04. This shows ISIAMOD could also be used here in the research area for water management both for rain-fed and irrigated agriculture.

4.4 Comparison of Models-Simulated and Field-measured Transpiration

Figure 4.8 shows the daily field-measured and models-simulated transpiration by SWAP and ISIAMOD models. Table 4.3 shows the statistics of the comparison between measured and simulated transpiration (T) models.

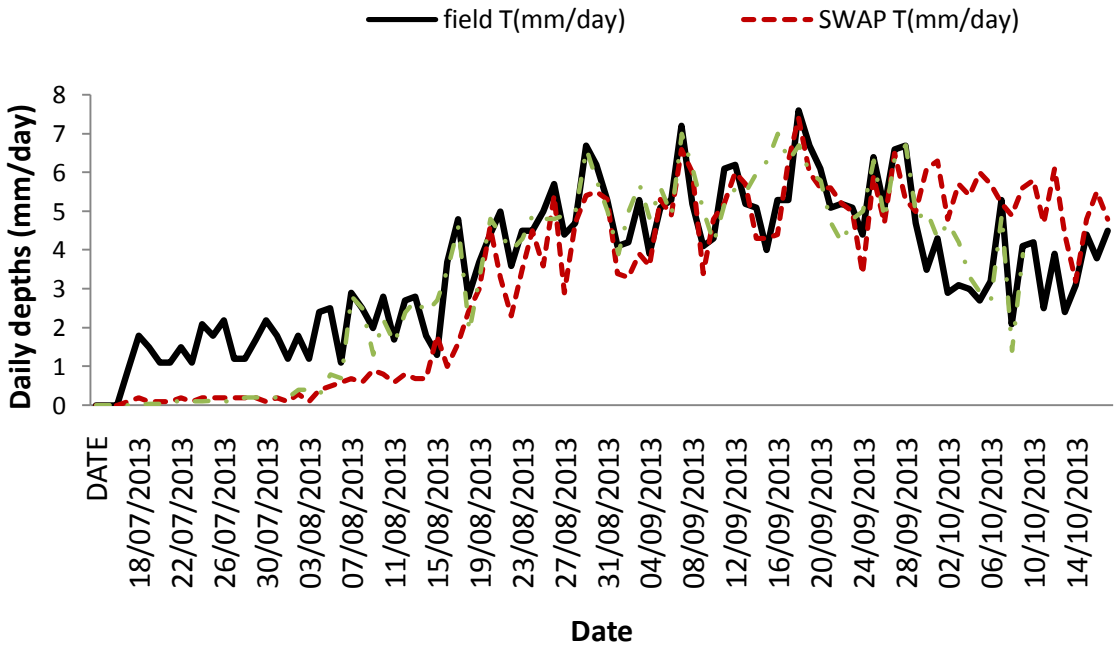


Figure 4.8: Daily measured and simulated transpiration by SWAP and ISIAMOD models

Table 4.5: Statistics of the comparison between simulated and measured transpiration (T)

Statistical performance indices	SWAP model Transpiration (T)	ISIAMOD model Transpiration (T)
AE	-0.34	-0.245
RMSE	0.583	0.86
CV (%)	17	24
EF	0.90	0.80
CRM	-0.097	0.0625

SWAP underestimated the crop transpiration (T) when the crops are still small. It overestimated it during the latter part of the crop's maturity growth stage, that is, during the peak of the growth when the canopy covers most of the soil. This difference is attributed to the disadvantage of considering the aerodynamic factor as multiplicative over crop growth, as assumed in Penman-Montheith equation for the estimation of both potential and actual ET, T and E in SWAP model. ISIAMOD, on the other hand, simulated the T fairly well except for the early growth stage where it also underestimated it, when the measured values are taken as the reference values. During the early crop growth stage when T is expected to be small, the mini-lysimeter could overestimate the T. So, the real T could be taken as the average of the three especially during the early growth stage of the crop.

The statistical indices in Table 4.5 reveal that, SWAP model has a tendency to over-predicts the T by 9% (CRM= 0.097), while ISIAMOD has a tendency to under-predicting the T by 6% (CRM= 0.0625). The modeling efficiency (EF) is 90% for SWAP and 80% for

ISIAMOD. These values (of EF) show a close relationship between the measured and simulated data and hence the prediction capacity of both models is good.

4.5 Comparison of Models-Simulated and Field-measured Evaporation

Figure 4.9 shows daily field measured evaporation (that is, ET-T) and simulated evaporation by SWAP and ISIAMOD models. Table 4.6 presents Statistics of the comparison between simulated and measured crop evaporation (E).

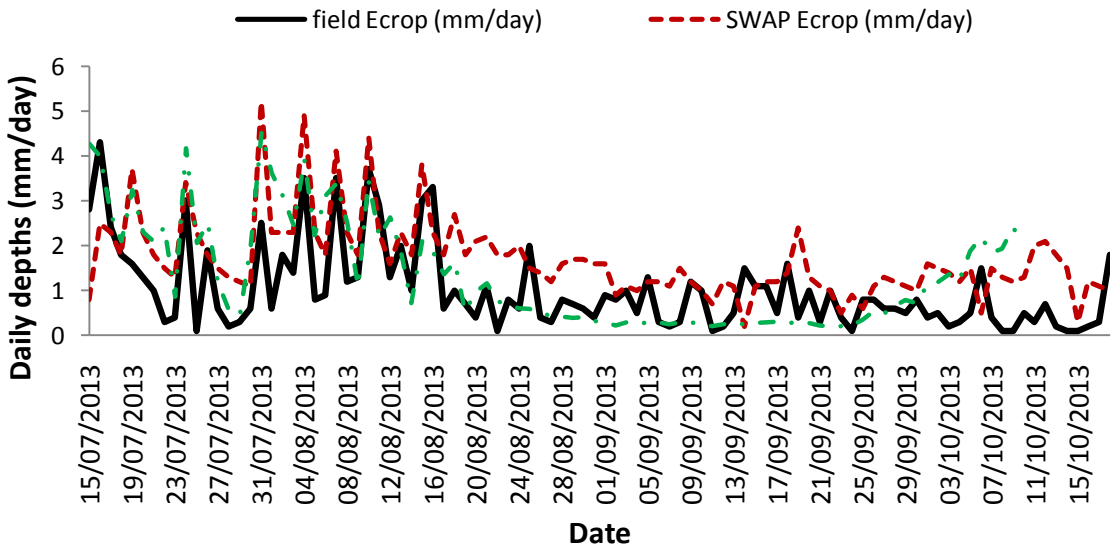


Figure 4.9: Daily measured and simulated evaporation by SWAP and ISIAMOD models

Table 4.6: Statistics of the comparison between simulated and measured crop evaporation (E)

Statistical performance indices	SWAP model Evaporation (E)	ISIAMOD model Evaporation (E)
AE	0.27	0.07
RMSE	0.29	0.33
CV (%)	41	29
EF	0.54	0.62
CRM	-0.21	-0.11

Figure 4.12 shows that, the cropped actual evaporation simulated by SWAP ranged from 3.7mm at the early crop growth stage (19/07/2013) to 0.2 mm toward the crop maturity stage (13/09/2013) with a seasonal total of 146.4 mm. The actual evaporation simulated by ISIAMOD ranged from 4.3 mm at the beginning of the crop season (15/07/2013) to 0.2 mm at the full vegetative stage of the crop (13/09/2013) with a seasonal total of 110.6 mm. SWAP overestimated the crop actual evaporation almost for the entire crop growth season. This is attributed to the fact that SWAP model assumes that the energy available for evaporation is entirely used to evaporate the intercepted water independent of the soil cover fraction. This could be valid for high soil cover fraction, that is, when the crop has fully matured and shield the ground. At small soil cover fraction (that is, at the early crop growth stage), this assumption might overestimate the actual evaporation rate of the intercepted water. ISIAMOD on the other hand, simulated the actual evaporation well except for the early crop growth stage where it overestimated it slightly. The actual evaporation in ISIAMOD depends on the moisture content of the soil.

Table 4.6 also shows that SWAP model overestimated the actual evaporation by 21%, while ISIAMOD only overestimate it by 11%. The modeling efficiencies was about 55% for SWAP and 62% for ISIAMOD, their coefficients of variability are 41% and 29%, respectively. ISIAMOD gave a better simulation of the actual evaporation than SWAP. Generally the performances of the two models are averagely okay because they compared favourably with several works performed using the models in literatures. The numerical values of the statistical indicators obtained also agreed with several agro-hydrological models reported in literature. For instance, Eitzinger*et al.*, (2004) compares three models (CERES, WOFOST and SWAP) in Marchfeld, Australia under different soil conditions in simulating soil water balance and reported a range of values of 2.32-6.77 % for RMSE. Cavero*et al.,* (2000) compared the performance of EPICphase, Modified EPICphase and CROPWAT models in Zaragoza, Spain and reported values of 1.51,-1.05, and 37 mm as average error of bias (AE) between simulated and measured seasonal evapotranspiration for the three models, respectively. They also obtained RMSE of 39.8, 38.6 and 69.6 mm for EPICphase, Modified EPICphase and CROPWAT, respectively. For the modeling efficiency (r^2), they reported values of 81, 81 and 77 % for the three models respectively.

4.6 Comparison of Measured and Simulated Surface Runoff and Deep Percolation

Figure 4.10 and 4.11; show the daily measured and simulated surface runoff and drainage by SWAP and ISIAMOD models.

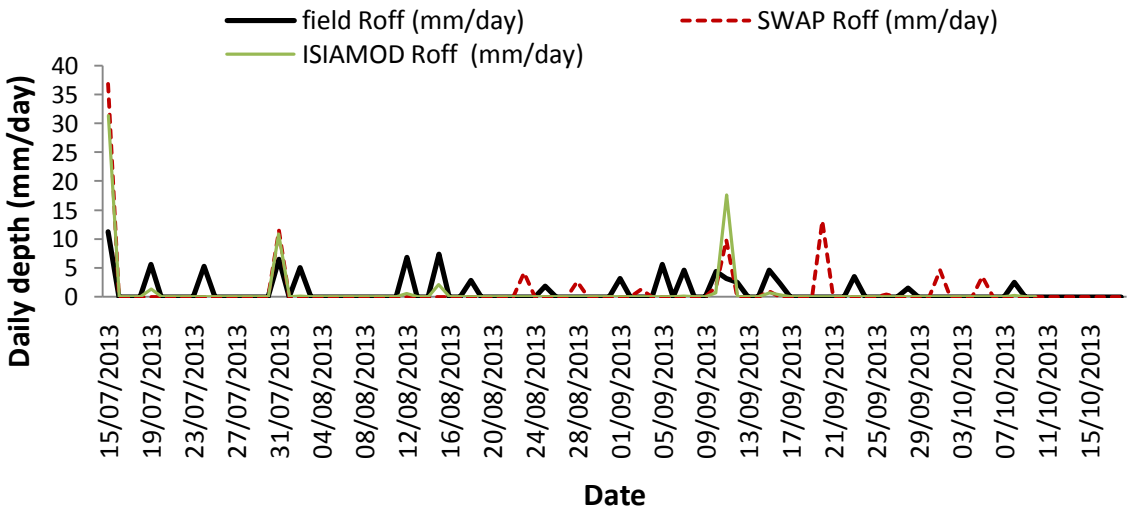


Figure 4.13: Daily measured and simulated surface runoff by SWAP and ISIAMOD models

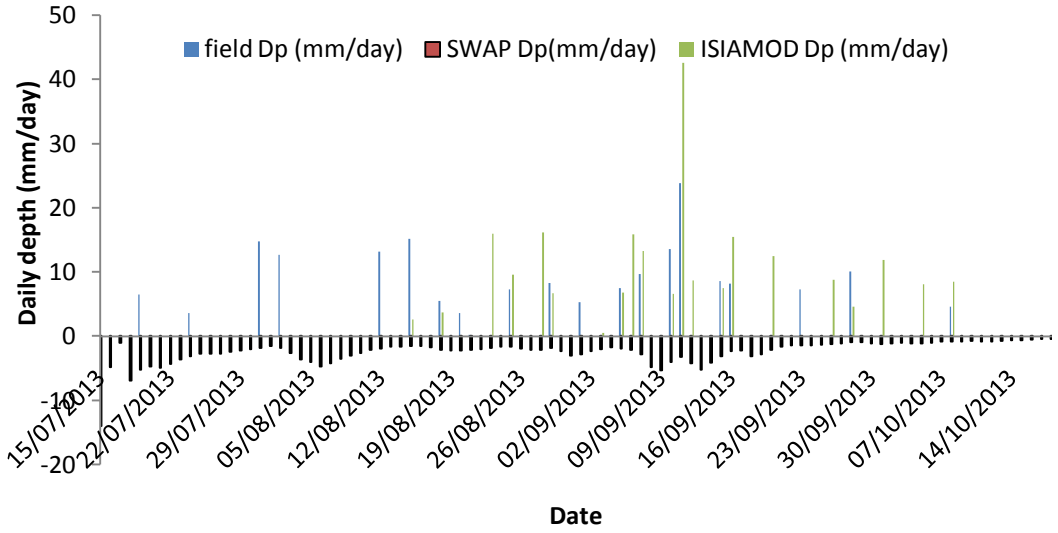


Figure 4.14: Daily measured and simulated drainage by SWAP and ISIAMOD models

SWAP determines if the soil water flux is directed upward (that is, capillary rise of water at the bottom of the soil profile) or downward (that is, flux of water out of the soil root zone). The downward flux in SWAP is given a negative value, as shown figure 4.14. ISIAMOD on the other hand only simulated a downward (which is positive) of water out of

the root zone. Since the lower boundary condition chosen for SWAP model is a lysimeter with free drainage bottom, all the drainage depths depicted in figure 4.14 are downward flow of excess water out of the root zone. The runoff and drainage from no-mulch lysimeter set-ups were used only to compare with the simulated runoff and drainage from the models. This was because the set-ups are more closely related to the soil-water-plant environments the two models are trying to simulate.

The runoff simulated by ISIAMOD varies from 1.29 to 36.9 mm with a seasonal total 65.9 mm; the runoff simulated by SWAP varies from 2.1 to 31.4 mm with a seasonal total of 91.2 mm. The drainage on the other hand, simulated by ISIAMOD varies from 2.6 to 42.5 mm with a season total of 217.6 mm; the drainage simulated by SWAP varies from 0.5 to 4.5 mm with a seasonal total of 226.1 mm.

The seasonal runoff from SWAP and ISIAMOD were about 12.7% and 9.2% of the total input water (rainfall + irrigation) respectively, while the seasonal deep percolation from SWAP and ISIAMOD was 31.5% and 30.4% of the total input water (rainfall + irrigation). Comparing with field measured values, SWAP overestimated the seasonal runoff by 0.3% while ISIAMOD under estimated the seasonal runoff by 3.2%.For the drainage, SWAP overestimated the seasonal drainage by 3.6% while ISIAMOD also overestimated the seasonal drainage by 2.5%. The differences between the models and the field measured data were insignificant, meaning that SWAP fairs well with ISIAMOD in estimating seasonal runoff and drainage. This result for seasonal runoff and drainage were similar to those in the literature. For example, Yin *et al.,* (2010) uses SWAP model and obtained similar result for seasonal water cycle under deficit irrigation in Beijing, China. Igbadun*et al.*, (2007) also

obtained a modeling efficiency of 70% while comparing the seasonal deep percolation for various irrigation treatments of maize crop in a traditional irrigation scheme in Tanzania.

Both SWAP and ISIAMOD poorly simulate the daily trends of runoff and drainage process as depicted in Figure 4.13 and 4.14, respectively. Drainage water was recorded by SWAP right from the first day of sowing, while ISIAMOD did not record any drainage water till 32 days after the crop sowing. Though, effort was made to repack the soil dug out from the field into the lysimeter tank in stratified order as it occurred in the field, but the various cracks and fissures that may exist in the natural soil profile cannot be created in the lysimeter tank. More so, the presence of wire-mesh and gravel in the bottom of the lysimeter tank could have affected the flux of water out of the lysimeter tank. Therefore, the wide disparity between lysimeter measured and the models-simulated deep percolation/drainage daily trends can be attributed to that. Also for SWAP, the soil database was use to estimate the soil hydraulic function, using the soil textural class and per cent organic matter content obtained from the field soil. Measuring the hydraulic functions parameters directly could have improves the daily trends of the deep percolation. Table 4.8 shows the summary of measured and simulated seasonal balance.

Table 4.8: Summary of Measured and Simulated seasonal soil water balance from planting to maturity

Soil Water Balance components	Lysimeter	ISIAMOD model	SWAP model
Potential evapotranspiration (mm)		408.9	430.9
Actual evapotranspiration (mm)	395.6	385.1	386.3
Potential transpiration (mm)		288.6	321.0
Actual transpiration (mm)	304.0	272.7	270.0
Deep percolation (mm)	200.1	217.6	226.1
Surface runoff (mm)	88.6	65.96	91.2
Precipitation (mm)	511.5	511.5	511.5
Irrigation (mm)	205	205	205

4.7 Measured and Simulated Crop Yield

Table 4.9 presents the measured crop yield both from field and lysimeters and that simulated by ISIAMOD. ISIAMOD simulates potential and actual crop yield and above-ground biomass yield. The actual yield simulated by ISIAMOD falls in the range of ±8 to 15%, while that of the above-ground biomass falls within 20 to 37%.

In SWAP,the simple crop model was used because of the reason already explained above. In the simple crop model of SWAP, only the relative crop yield was simulated with the crop response factor taking as 1. This yield an equation for the actual yield (Y_a) to potential yield (Y_p) of $Y_a=0.84*Y_p$.

Table 4.9: Measured and simulated crop yield of the maize (*SAMMAZ-28*)

	Grain yield (t/ha)	above-ground Biomass (t/ha)
Actual yield (field)	5.44	13.66
Potential yield (field)	-	-
Actual yield (ISIAMOD)	5.79	8.53
Potential yield (ISIAMOD	5.87	8.64
SWAP	-	-
Lysimeter with mulch	6.78	12.75
Lysimeter without mulch	5.00	10.98

4.8 Comparison of the Performance of SWAP and ISIAMOD

Table 4.10 presents the comparison of the models based on their ability to simulate the soil water balance components of the maize field crop. Table 4.9 presents summary of comparison of the two models in terms of their ability to simulate soil water balance components. The note at the base of the table explained the performance rating.

Table 4.10: Performance of ISIAMOD and SWAP in this specific studies

Predicted	**ISIAMOD**	**SWAP**
Evapotranspiration (ET)	++	++
Transpiration (T)	++	++
Evaporation (E)	++	+
Drainage/deep percolation (D_p)	+	+
Runoff (R)	+	+
Yield	++	+

Note: ++ satisfactory, and + Good

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary

A field experiment was conducted during 2013 rainy season at the Department of Agricultural Engineering research field, Ahmadu Bello University, Samaru, Nigeria, to generate data to test the ability of two agro-hydrological models (SWAP and ISIAMOD) in simulating the soil water balance of a cropped field under rainfall condition. The field experiment consists of nine weighing-type mini-lysimeter; which comprises of three treatments replicated three times. The treatments are: mulch cropped lysimter to measure the process of transpiration, no-mulch cropped lysimeter to measure evapotranspiration process, and no-crop lysimeter set-up to measure the process of evaporation from bare soil. The lysimeters were installed in a field of size 0.053ha. Both the field and the lysimeters were planted with maize crop variety (Sammaz-28) and were all given the same agronomical attention. Soil moisture was monitored in the field throughout the crop growing season with gypsum blocks installed within the crop rooting zone. Soil water balance components were measured directly from the lysimeters. Grain yields and above-ground biomass yield were also measured from both the field and the lysimeters. The inputs of the two models were obtained from the field (that is, for soil and crop data) and Institute for Agricultural Research's (I.A.R) meteorological station (that is, for the weather data). The models' simulated data were compared with the field measured data statistically.

5.2 Conclusion

From the study, the following conclusions were reached:

(1) The soil water balance components estimated with the lysimeters compared well with those of the field, which implied that the mini-lysimeter effectively estimated the Soil water balance of the cropped field.

(2) The two models satisfactorily predicted daily evapotranspiration (ET), transpiration (T) and evaporation (E) from the cropped field. The modeling efficiencies of the two models ranged from 84 to 90%, except for evaporation process of 54 to 62%.

(3) However, SWAP model overestimated ET, T and E components of the above soil water balance slightly during the vegetative to maturity growth stages of the crop, while ISIAMOD gave a better estimate during these growth stages except for early growth stage where it overestimated these components. On average, the statistical indicator used (CRM) shows that the tendency of ISIAMOD to underestimate ET, T and E falls in the range of 2.5 to 6.0% while the tendency of SWAP to overestimate ET, T and E falls in the range of 2.0 to 9%.

(4) The two models could only simulate the seasonal run-off and drainage, but could not simulate the daily trends of the run-off and drainage processes.

5.3 Recommendation

The following are recommended from the work:

(1) The two models can be used for determination of soil water balance components of cropped soil and for analyzing a better water management option for agricultural production.

(2) The performance of these models can also be tested during dry season because of difference in micro-climate with seasonal variation, and for different crops in the same study area to expand its application in the area.

(3) For the SWAP model, on-field estimation of the soil hydraulic parameters than using the soil data-based (in-built in the model) could give a better prediction of the daily trend of deep percolation, and hence the surface runoff.

(4) Construction of a permanent weighing-lysimetre in the Department of Agricultural Engineering to enable detailed study of the various modules of the models.

REFERENCES

Allen, R.G., Piereira, L.S. Raes, D. and Smith, M. (1998). Crop evapotranspiration: Guidance for Computing crop water requirements. *F. A. O irrigation and Drainage paper 56. Food and Agriculture Organization of United Nations.*

Aworidhe, I.E. (2011). Estimation of evapotranspiration of rain fed maize crop using weighing micro-lysimeter. Unpublished project summited to the Department of Agricultural Engineering, Ahmadu Bello University, Zaria, Kaduna State, Nigeria.

Awujoola, A.T. (1979). Soil Mapping and Soil Characterized Studies in the Zaria Area. M.Sc.Thesis A.B.U, Zaria, Nigeria.Pp: 150.

Belman, C, Wesseling, J.G. and Feddes, R.A. (1983). Simulation of the water of a cropped soil: SWATRE. Journal of Hydrology. 63, 271-286.

Bouten, W.(1992). Monitoring and modelling forest hydrological processes in support of acidificationresearch. PhD-thesis, University of Amsterdam, 218 p.

Cadoni, P., Angelucci, F. (2013).Analysis of Incentives and Decentives for maize in Nigeria. Technical notes series, *Monitoring African Food and Agriculture &Suivi des Politiquesetalimmrntraires en Africque (MAFAP & SPAAA), FAO. ROMe.*

Campbell, G.S. and Diaz,R.(1988). Simplified soil-water balance models to predict crop transpiration In: Bindinger, F.R., Johansen, C., (eds), Drought *Research Priorities for the Dryland Tropics. Parancheru, A.P. 502324, India*: ICRISAT, pp.15-25.

Cavero, J., Inme, F., Philippe, D. and Jose, M.F. (2000). Simulation of Maize Yield under Water Stress with EPICphase and CROPWAT Models. *Agronomy Journal. 92:679-690.*

Clark, G.A., Reddel, D.L., Adams,R.F, andMcDurnie, J.C. (1984). "Evolution of Mini-Lysimeters for Deficit Irrigation Studies": American Society of Association Executive (ASAE).Technical paper, 84 – 2621.

Crookston, M.A. (2011). Utilizing Soil Moisture Readings in Irrigation Scheduling.*Proceedings of the 23rd Annual Central Plain Irrigation Conference, Burlington, Co. Available from CPIA, 760N. Thompson. Colby, Kansas.*

Dugas, W.A. and W.L. Bland.(1989). "The Accuracy of Evaporation Measures from Small Lysimeters". *Agricultural Forest Meteorology. 46:109-119.*

Doorenbos, J. and Kassam, A.H (1979). Yield Response to Water. FAO report 33. *Rome: Food And Agricultural Organizations.*

Duretz, S., Drouet, J.L., Durand, P., Hutchings, N.J., Theobald, M.R., Salmon-Monviola, J., Dragosits, U., Maury, O., Sutton, M.A. and Cellier, P. (2011). NitroScape: a model to integrate nitrogen transfers and transformations in rural landscapes. *Environmental Pollution 159 (11), 3162e 317 0.*

Dwyer, L.M., Stewart, D.W. (1986). Leaf Area Development in field–grown maize.*Agronomy Journal*. 78, 334-343.

Ejieji C.J, Fasasi M.B (2003). Development of asoil water sensor using gypsum block and a multi-meter. *Journal Agricultural Resources*. Dev. 2:89-92.

Federer, C. A. (1996). Inter-comparison of methods for calculating potential evaporation in regional and global water balance models. *Water Resources Research*, vol. 32, No. 7, pp3215-2321, July 1996.

George, W. T. (2005). Estimating the Crop Coefficient of Bahiagrass Using Lysimeter and the FAO-56 Penman-MonteithEquation.An unpublished thesis.University of Florida.

Goudriaan, J.(1977). Crop meteorology: A simulation study. Simulation monographs, Pudoc,Wageningen.

Hartmann, R. (1990).Measurement of Field Water Balance. Department of Soil Management and Soil Care, International Centre for Eremology, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium. www.google.com. 12/01/2013.

Hillel, D. (1971). Soil and Water: physical principles and processes. *Environmental Soil Physics.*Academic press, New York.

Hoyningen-Hüne, J.von.(1983). Die Interzeption des Niederschlags in landwirtschaftlichenBeständen.Schriftenreihe des DVWK 57: 1-53.

Howell, T. A., Schneider,A. D. and Jensen, M. E. (1991). History of lysimeterdesign and use for evapotranspiration measurements.pp. 1-9. In: Allen, R. G., Howell, T. A., Pruitt, W. O., Walter, L A., and Jensen, M. E. (Editors). Lysimeters for Evapotranspiration and Environmental Measurements. *Proceedings of the ASCE International Symposium on Lysimetry, Honolulu, HA, ASCE,* New York.

Hutchings, N.J., Dalgaard, T., Rasmussen, B.M., Hansen, J.F., Dahl, M., Jörgensen, L.F., Ernstsen, V., von Platen-Hallermund, F. and Pedersen, S.S. (2004).Watershed nitrogen modeling. In: Hatch, D.J., Chadwick, D.R., Jarvis, S.C., Roker, J.A .(Eds.), Controlling Nitrogen Flows and Losses.Wageningen Academic Publishers, pp. 47e 53.

Igbadun, H.E. (2006). Evaluation of Irrigation Schedu ling Strategies for Improving Water Productivity: Computer-based Simulation Model Approach. PhD Thesis Sokoine University of Agriculture, Morogoro, Tanzania.

Igbadun, H. E, Mahoo, H. F, Tarimo, A.K.P.R. and Salim, B. A. (2007). "Simulation of Soil Moisture Dynamics of the Soil Profile of a Maize Crop under Deficit Irrigation

Scheduling" . *Agricultural Engineering International: the CIGR Ejournal*. Manuscript LW 06 015. Vol. IX.

Igbadun, H. E. (2008). Effect of Deficit Irrigation Scheduling on yield and soil water balance of irrigatedmaize.*Irrigation Science*. 27: 11-23.

Igbadun, H. E. (2012a). Estimation of Crop Water Use of Rain-fed Maize and groundnut using Mini-Lysimeter.*The Pacific Journal of Science and Technology.Vol.13 No. 1 (spring).*

Igbadun, H. E. (2012b). Irrigation Scheduling Impact Assessment Model (ISIAMOD): A decision tool for irrigation scheduling. *Indian Journal of Science and Technology.Vol. 5 No. 8. ISSN: 0974-6816.*

Ines, A. V. M.,Droogers, P., Makin, I. W. and Das Gupta, A. (2001). Crop growth and soil water balance modeling to explore water management options. (International Water Management Institute.) *IWMI Working Paper 22. Colombo, Sri Lanka:*

Inman-Bamber N.G., McGlinchey M.G. (2003): Crop coefficients and water-use estimates for sugarcane based on long-term Bowen ratio energy balance measurements. Field Crops Research, 83: 125–138.

Isard, S.A. and M.J. Belding.(1989). "Evapotranspiration from the Alpine Tundra of Colorado, USA". Arctic Alpine Res. 21:71-82.

IITA (2003).*Nigeria food Consumption and Nutrition Survey,* 2001-2003 Summary.

Johannes, H., Margarita, V., Alain, B (2001). *Approach to Soil Water Modeling*: Tools and data Considerations to provide relative soil water information for deficit irrigation.

Jones CA and Kiniry JR (1986) CERES- Maize: Asimulationmodel of maize growth and development.Texas A & M Univ. Press, College Station, Texas, pp:150.

Klinkiberg, K. and Higgins, G. M. (1968): An Outline of Northern Nigeria Soils. *Nigerian Journal of Science*. 2: 91 – 115.

Lascano, R. (1991). Review of models for predicting soil water balance. Soil water Balance in the Sudano-Sahelian Zone. Proceedings of the Niamey Workshop, Februay ,1991. IAHS Publ. NO.199, 1991.

Mahdian, M. H. and Gallichard, J. (1995).Validation of the SUBSTOR model for simulating soil Water content.Trans. *American Society Agricultural Engineers* (ASAE). 38, 513-520.

Majumdar, D. K. (2006). Irrigation Water Management: Principle and Practice. Estimating Water Requirement of a Crop.*Eastern Economic Edition*.New Delhi Indian.

Malone, R.W., Bonta, J.V., Stewardson,D.J. andNelsen, T.(2000). "Error Analysis and Quality Improvement of the Cosheton Weighing Lysimeters". Trans.*American Society of Agricultural Engineers* (ASAE). 31:477-484.

Maruyama A., Ohba K., Kurose Y., Miyamoto T. (2004): Seasonal variation in evapotranspiration from mat rush grown in paddy field. Journal of Agricultural Meteorology, 60: 1–15.

McCown, R. L, Hammer, G. L, Hargreaves, J. N. G., Holzworth, D. P and Freebairn, D. N. (1996). APSIM: a novel software system for model development, model Testingand simulation in agricultural Research.*Agricultural System.*50, 255-271.

Michael, A.M. (1999). *Irrigation Theory and Practice*.Reprint.Vikas Publishing House PVT Ltd. New Delhi, pp 520.

Michael, B. A. (2011). Estimation of crop water use of groundnut under rain fed condition. Unpublished project summited to the Department of Agricultural Engineering, Ahmadu Bello University, Zaria, Kaduna State, Nigeria.

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media.*Water resource Research*, 12: 513-523.

Muthuri, C. W. (2004). Models. In:*The Green Book*," A Guide to Effective Graduate Research in African Agriculture, Environment and Rural Development" by, Patel K. B., Muir-Leresche, K., Coe R. and Hainsworth, S.D. African Crop Science Society Kampala Uganda; pp 213-224.

Odofin, A. J., Egharevba,N. A.,Babakutigi, A. N. and Eze, V. (2012). Drainage beyond maize root zone in an Alfisol subjected to three land management system at Minna, Nigeria. *Journal of Soil Science and Environmental Management*. Vol. 3(9), pp. 216-223. ISSN 214-2391.

Panda, R.K., S.K. Behera and P.S. Kashyap.(2004). Effective management of i rrigation water for maize under stress conditions. *Agricultural Water management.* 66: 181-203.

Plauborg, F., M.N. Andersen, T. Heidmannand Olsen, J.E. (1996). MARKVAND: an irrigation scheduling system for use under limited irrigation capacity in a temperate humid climate. In: *Irrigation Scheduling from Theory to Practice*. Water Reports 8. FAO-ICID-CIID, Rome, pp. 177-184.

Poss, J. A., Russell, W. B., Shouse, P. J., Austin, R. S., Grattan, S. R., Grieve, C. M., Lieth, J. H.,Zeng, L. (2003). A volumetric Lysimeter System (VLS): an alternative to weighing lysimeter for plant-water relation studies. *Computer and Electronics in Agriculture*, 43(2004)55-68.

Qureshi, S. A. and Madramootoo, C. A. (2001).Modeling the Soil Water Balance of a Sugarcane Crop in Sindh, Pakistan with SWAP93.*Canadian Water Resources Journal*.Vol. 26,No.1.

Rafael, M. F., João, B. D., Eloiza, M. C. D. and Fabo, A.B. (2011). Lysimeter Soil Water Balance Evaluation for an experiment developed in southern Brazilian Atlantic forest region. *Hydrological Processes*.Published online, Wiley online Library. DOI: 10.1002/hyp.7971.

Ritchie, J.T.(1972). Model for predicting evaporation from a row crop with incomplete cover. *Water Resource Research*. 8: 1204-1213.

Rosental, W.R., Arkin,G.F and Shouse.P.J.(1985). "Water Deficit Effects on Sorghum Transpiration". National Conference on Advances in Evapotranspiration. American Society of AgriculturalEngineeris (ASAE): St. Joseph, MI. 159- 169.

Schwab, G.O., Fangmeier, D.D., and Elliot, W.J. (1993). Water erosion and Control Practices: *Soil and Water Conservation*. John Willey and son.Inc.

Schneider, A.D. and Howell, T.A. (1991). Large, monolithic, weighing lysim e ters. pp. 37-45 in Allen, R. G., Howell, T. A., Pruitt, W. O., W a lter, LA., and Jensen, M. E. (Editors). Lysimeters for evapotranspiration an d environmental measurements. *Proceedings of the American Society Commission Executives (ASCE). International Symposium onLysimetry, Honolulu*, HA, ASCE, New York, NY.

Stockle, C. O and Nelson, R. (1996).Copping system simulation model.User's Manual. *Biological System EngineeringDeptetment*. Washington State Uni., Pullman WA 99164-6i20. pp: 165.

Steduto, P., T.C. Hsiao, D. Raes, and Fereres, E. (2009). AquaCrop —The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agronomy Journal. 101:426 – 437 (this issue).

Tsuji, G.T.,Uehara, G. and Salas,S.(1994). *Decision Support System for Agro-technology Transfer (DSSAT v3.0)*. Honolulu, Hawaii: University of Hawaii.

Uzonwa, T.C. (1991). "The Lysimeter Determination of Consumptive Use of Wheat". A final year project report submitted to the Department of Agricultural Engineering Technology, Federal Polytechnic: Bauchi, Nigeria.

Van Heemst, H.D.J. (1988). Plant values required for Simple crop growth Simulation models: reviewandbiolography. *Simulation Report CABO-TT nr.17. Wageningen*.

Van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L.Y. and Goudrian, J. (2003). On approach and application of Wegenningen crop models. *European Journalof Agronomy*. 18: 201-234 pp.

Van Genuchten, M.Th. (1980). A close form equation for predicting the hydraulic Conductivity of unsaturated soil.*Soil Science Societyof American Journal*. 44,892-898.

Van Dam, Huygen, J.C., Wesseling, J.,Feddes, J.G, Kabat, R.A., van Waslum, P., Groenendjik, P.E.V, PP, and van Diepen, C.A (1997). Theory of SWAP version Version 2.0: simulation of water flow and plant growth in the soil-water-Atmosphere-plant environment. *Technical document 45. The Nethland: WageningAgr. Uni. Eng*. 32, 497-513.

Vesna, Z., Nolz,R.,Cepuder,P. B., Bra,Či.,Železnik,Č.,Pintar, M. (2012). Determination of water balance components with high precision weighing lysimeter in Kleče. DOI: 10.2478/v10014-012-0016-1. *Agricultural category code*: p10.

Watanabe K., Yamamoto T., Yamada T., Sakuratani T., Nawata E., Noichana C., Sributta A., Higuchi H. (2004): Changes in seasonal evapotranspiration, soil water content, and crop coefficients in sugarcane, cassava, and maize fields in Northeast Thailand. *Agricultural Water Management*. 67:133–143.

Wight, J.R., Hanson,C.L. and Cooley.K.R. (1986). "Modeling Evapotranspiration from Sage bush-Grass Rangeland". *Journal of Ranging Management*. 39:81-85.

Whitehead, P.G., Wilson, E.J., Butterfield, D., (1998). A semi distributed integrated nitrogen model for multiple source assessment in catchments (INCA): Part I-model structure and process equations. *Science of the Total Environment* 210/211, 547 e558.

Wösten, J.H.M., Lilly,A.,Nemes, A. and Le Bas,C.(1998). Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning. Report 156, Winand Staring Centre, Wageningen, Netherlands.

Wright, I. R. (1990).A lysimeter for measurement of evaporation from high altitude grass.*Proceedings of two Lausanne Synposia*. IAHS Publication.no 193.

Williams, J. R, Jones, C. A, Kiniry and Spanel, D. A. (1989). The EPIC crop growth Model.Trans. American Society Agricultural Engineering. 32, 497-513.

Ying, M. A., Shaoyuan, F., Zailin, H., Xianfang, S. (2010). Application of the SWAP model to simulate the field water cycle under deficit irrigation in Beijing, China.ScienceDirect.*www.elsevier.com*

Zhang, Y., Yu,Q., Liu,C. Jiang, J. and Zhang, X.(2004). Estimation of winter wheat evapotranspiration under water stress with to semi-empirical approach.*Agronomy Journal 96*, 159-168.

Zoubeida, K. B. (2012). Estimation of Evapotranspiration Using Soil Water Balance Modelling.Remote Sensing and Modeling, Ayse Irmak (eds). Twis El Manar University. Tunisia.

APPENDIX A

INPUT FILES OF ISIAMOD andSWAP MODELS

Weather Data Used the Two Models (SWAP and ISIAMOD)

STATION	DAY	MONTH	YEAR	RAD MJ/m^2	$T_{min.}$ °C	$T_{max.}$ °C	HUM kPa	WIND m/s	RAIN mm
ABUS	15	7	2013	23.6	23	31	2.64	1.37	86.5
ABUS	16	7	2013	24.1	25	31	2.72	2.16	6.4
ABUS	17	7	2013	23.8	23	32	2.67	1.56	0
ABUS	18	7	2013	20.2	21	29	2.47	1.67	0.9
ABUS	19	7	2013	21.6	24	29	2.59	1.77	17.9
ABUS	20	7	2013	16.1	21	28	2.42	1.17	0
ABUS	21	7	2013	20.3	22	29	2.61	1.61	1.4
ABUS	22	7	2013	12.8	24	32	2.76	1.58	0
ABUS	23	7	2013	18.8	24	33	2.76	1.97	0
ABUS	24	7	2013	23.8	22	30	2.50	1.91	15
ABUS	25	7	2013	19.9	24	30	2.99	2.38	0
ABUS	26	7	2013	17.3	20	29	2.17	2.26	2.2
ABUS	27	7	2013	20.3	24	31	2.92	1.86	0
ABUS	28	7	2013	11.3	23	28	2.60	2.16	0
ABUS	29	7	2013	21.0	23	30	2.90	2.04	0
ABUS	30	7	2013	13.2	24	31	2.98	2.16	1.2
ABUS	31	7	2013	25.0	21	31	2.44	1.66	39.8
ABUS	1	8	2013	19.5	24	30	2.69	2.18	0
ABUS	2	8	2013	18.7	23	28	2.51	2.15	19.9
ABUS	3	8	2013	18.5	23	30	2.49	1.79	0
ABUS	4	8	2013	22.9	23	31	2.90	1.67	0
ABUS	5	8	2013	17.5	23	26	2.29	2.37	0
ABUS	6	8	2013	11.9	23	32	2.85	1.78	0
ABUS	7	8	2013	21.1	23	30	2.87	1.99	3.5
ABUS	8	8	2013	18.7	22	32	2.82	1.82	0
ABUS	9	8	2013	12.0	23	30	2.57	1.67	0
ABUS	10	8	2013	24.6	21	30	2.34	2.00	4.7
ABUS	11	8	2013	14.5	20	30	2.50	2.12	0
ABUS	12	8	2013	17.9	20	28	2.24	1.44	17.9
ABUS	13	8	2013	12.4	22	30	2.60	1.59	0
ABUS	14	8	2013	17.0	22	25	2.46	1.87	0
ABUS	15	8	2013	11.9	22	29	2.51	2.17	24.5
ABUS	16	8	2013	17.0	23	30	2.89	1.65	2.7
ABUS	17	8	2013	14.1	23	28	2.92	1.66	3.1
ABUS	18	8	2013	13.2	22	32	3.01	0.87	8.7
ABUS	19	8	2013	19.5	23	25	2.64	1.40	0.7
ABUS	20	8	2013	13.3	22	28	2.50	1.21	5.9

ABUS	21	8	2013	14.5	22	31	2.94	1.90	2.8
ABUS	22	8	2013	22.2	23	30	2.82	1.62	0
ABUS	23	8	2013	22.3	22	28	2.44	1.69	0
ABUS	24	8	2013	13.5	24	30	2.79	1.51	0
ABUS	25	8	2013	20.4	20	29	2.42	1.12	13
ABUS	26	8	2013	15.9	23	31	3.01	0.88	0
ABUS	27	8	2013	21.4	23	31	3.01	0.79	3.5
ABUS	28	8	2013	17.5	22	30	2.54	1.22	2
ABUS	29	8	2013	20.9	23	30	2.63	1.96	9.9
ABUS	30	8	2013	23.3	23	33	2.78	1.43	0.6
ABUS	31	8	2013	21.9	23	30	2.44	1.47	2.8
ABUS	1	9	2013	18.6	22	30	2.20	1.20	11.5
ABUS	2	9	2013	13.2	24	29	2.75	0.69	0.2
ABUS	3	9	2013	19.9	22	31	2.49	0.65	0
ABUS	4	9	2013	19.3	22	32	2.86	1.08	0
ABUS	5	9	2013	20.6	23	30	2.56	1.15	14.9
ABUS	6	9	2013	20.7	21	31	2.40	1.20	1.4
ABUS	7	9	2013	20.6	23	31	2.45	0.70	15.2
ABUS	8	9	2013	22.3	23	33	2.44	1.37	0
ABUS	9	9	2013	20.9	22	32	2.69	1.73	0
ABUS	10	9	2013	20.7	22	30	2.42	1.19	26
ABUS	11	9	2013	13.7	21	27	2.54	1.27	66.3
ABUS	12	9	2013	22.2	22	30	2.44	1.44	0
ABUS	13	9	2013	21.0	23	32	2.71	1.28	0
ABUS	14	9	2013	20.9	23	32	2.52	1.24	0
ABUS	15	9	2013	21.0	20	32	2.34	1.08	26.2
ABUS	16	9	2013	23.3	22	34	2.55	1.12	16.6
ABUS	17	9	2013	22.8	22	35	2.72	1.44	0
ABUS	18	9	2013	21.0	23	34	2.41	1.40	0
ABUS	19	9	2013	22.0	22	35	2.41	1.43	0
ABUS	20	9	2013	22.7	23	34	2.41	1.04	0
ABUS	21	9	2013	18.6	24	31	2.59	1.12	0
ABUS	22	9	2013	20.1	20	28	2.07	1.05	0
ABUS	23	9	2013	14.5	23	29	3.09	1.01	10.4
ABUS	24	9	2013	21.4	23	28	2.48	0.93	0
ABUS	25	9	2013	15.2	20	30	2.74	0.91	0
ABUS	26	9	2013	23.6	20	33	2.58	1.39	0
ABUS	27	9	2013	22.0	22	30	2.25	1.33	0
ABUS	28	9	2013	24.1	20	30	2.25	1.33	17
ABUS	29	9	2013	23.0	20	31	2.29	0.98	0
ABUS	30	9	2013	22.5	21	34	2.61	1.01	0
ABUS	1	10	2013	24.8	24	33	2.48	1.18	0
ABUS	2	10	2013	19.4	23	34	2.31	1.00	0
ABUS	3	10	2013	20.0	23	33	2.61	1.22	0
ABUS	4	10	2013	23.7	22	34	2.70	1.09	0
ABUS	5	10	2013	23.0	22	33	2.52	1.16	0

ABUS	6	10	2013	23.3	23	33	2.42	1.00	0
ABUS	7	10	2013	20.5	22	33	2.32	1.08	0
ABUS	8	10	2013	16.6	22	32	2.51	1.14	22.3
ABUS	9	10	2013	17.9	23	28	2.32	0.98	0
ABUS	10	10	2013	20.0	23	32	2.59	1.01	0
ABUS	11	10	2013	23.7	20	32	1.70	1.32	10.9
ABUS	12	10	2013	21.3	23	32	1.66	1.00	0
ABUS	13	10	2013	20.6	18	34	1.14	0.87	0
ABUS	14	10	2013	19.0	19	33	1.33	0.82	0
ABUS	15	10	2013	24.0	22	30	1.76	0.80	0
ABUS	16	10	2013	24.3	20	32	2.05	0.93	0
ABUS	17	10	2013	24.3	22	34	1.89	1.18	0
ABUS	18	10	2013	23.3	18	34	1.36	1.11	0

Table: Crop and other input parameters for the ISIAMOD model

Parameter	value
Plant date	15/07/2013*
Seed emergence date	18/07/2013*
Maturity date	18/10/2013*
Maximum rooting depth	0.76 m*
Maximum leaf area index (LAI)	4.9 m^2/m^2*
Radiation Use Efficiency (RUE) for vegetative and flowering stages	2.3 g/MJ**
Radiation Use Efficiency (RUE) for the grain filling stages	2.3 g/MJ**
Harvest index (non-water stress)	0.68**
Peak crop coefficient	1.3*
Radiation extinction factor	0.65**
Base temperature	8^oC
Optimum temperature	30.0^oC
Fraction of growth stage duration at which LAI decline starts	0.80
LAI parameter “a”	1120
LAI parameter “b”	17.2
LAI adjustment factor	1.0
Harvest index adjustment factor for the flowering stage	0.55
Harvest index adjustment factor for the grain filling growth stage	0.55
Days of planting at which establishing growth stage starts (zero)	0*
Days of planting at which vegetative growth stage starts	18*
Days of planting at which flowering growth stage stats	41*
Days of planting at which grain filling growth stage starts	63*

*= data obtained from field experimental data;

** = final values obtained through model calibration

Irrigation Input Data for Both the Models

Date	Depth (mm)
04/08/2013	20.0
23/08/2013	30.0
28/08/2013	25.0
03/09/2013	25.0
06/09/2013	20.0
20/09/2013	40.0
26/09/2013	25.0
01/10/2013	30.0
05/10/2013	30.0

Crop Parameters for SWAP model

Extinction factor for diffuse visible light						0.62		
Extinction factor for direct visible light						0.64		
DVS*	0.00	0.30	0.50	0.60	0.80	1.00	1.30	2.00
LAI	0.07	0.15	0.45	0.75	3.2	4.30	4.90	3.75
Crop height (cm)	2.00	16.0	30.00	43.00	150.00	160.00	170.00	180.00
Rooting depth (cm)	5.00	15.00	20.00	43.00	55.00	55.00	75.00	76.00

* The development stages (DVS) are as explained in van Heemst (1988).

Soil Input Data for ISIAMOD model

Number of soil profile layer	5
Curve number	75
Bare soil evaporation coefficient	1.05
Soil transpiration coefficient	0.018 m/day

Layer	Thickness (m)	No. of compartment in the layer	Volumetric soil moisture content @ FC (m^3/m^3)	Volumetric soil moisture content @ PWP (m^3/m^3)	Volumetric soil moisture content @ planting (m^3/m^3)	Dry bulk density	Wet bulk density	% sand
1st	0.10		0.383	0.197	0.113	1.39	1.633	56
2nd	0.20		0.355	0.180	0.123	1.30	1.525	60
3rd	0.15		0.366	0.186	0.114	1.37	1.636	60
4th	0.15		0.374	0.274	0.135	1.34	1.604	56
5th	0.16		0.356	0.289	0.123	1.40	1.716	60

Calibrated soil hydraulic parameter of the soil profile from SWAP model*

Soil series		Layer (cm)	Θ_s (cm^3cm^{-3})	Θ_r (cm^3cm^{-3})	K_s (cmd^{-1})	α (cm^{-1})	λ (-)	n (-)
Top soil	organic	0-10	0.766	0.010	8.000	0.013	-0.400	1.204
	Medium fine	10-30	0.430	0.010	2.272	0.0083	-0.588	1.254
	Medium fine	30-45	0.439	0.010	12.061	0.0314	-2.342	1.181
Subsoil	medium	45-60	0.412	0.010	4.000	0.0082	-0.500	1.218
	medium	60-80	0.392	0.010	10.755	0.0249	-0.744	1.169

*The dataset of the soil physical characteristics in SWAP model soil database is based on the Staring Series (Wösten et al., 1994).

APPENDIX B

SWAP model's soil water balance results

* Water balance increments (cm/period)

Date	Day	Rain	Irrig	Interc	Runoff	Transpiration		Evaporation		Drainage	Q Bottom
*dd/mm/yyyy	nr	gross	gross	pot	act	pot	act	net	net		
15/07/2013	15	8.650	0.000	0.000	6.699	0.000	0.000	0.084	0.084	0.000	-2.397
16/07/2013	16	0.640	0.000	0.000	0.000	0.000	0.000	0.575	0.550	0.000	-1.480
17/07/2013	17	0.000	0.000	0.000	0.000	0.000	0.000	0.547	0.228	0.000	-1.014
18/07/2013	18	0.090	0.000	0.000	0.000	0.011	0.011	0.415	0.175	0.000	-0.691
19/07/2013	19	1.790	0.000	0.001	0.000	0.023	0.002	0.468	0.468	0.000	-0.517
20/07/2013	20	0.000	0.000	0.000	0.000	0.012	0.011	0.366	0.228	0.000	-0.472
21/07/2013	21	0.140	0.000	0.001	0.000	0.013	0.013	0.416	0.175	0.000	-0.492
22/07/2013	22	0.000	0.000	0.000	0.000	0.013	0.013	0.359	0.147	0.000	-0.426
23/07/2013	23	0.000	0.000	0.000	0.000	0.020	0.020	0.509	0.130	0.000	-0.362
24/07/2013	24	1.500	0.000	0.002	0.000	0.017	0.007	0.440	0.440	0.000	-0.310
25/07/2013	25	0.000	0.000	0.000	0.000	0.024	0.023	0.540	0.228	0.000	-0.271
26/07/2013	26	0.220	0.000	0.002	0.000	0.017	0.017	0.393	0.175	0.000	-0.272
27/07/2013	27	0.000	0.000	0.000	0.000	0.023	0.023	0.474	0.147	0.000	-0.267
28/07/2013	28	0.000	0.000	0.000	0.000	0.015	0.015	0.285	0.130	0.000	-0.248
29/07/2013	29	0.000	0.000	0.000	0.000	0.021	0.021	0.399	0.117	0.000	-0.227
30/07/2013	30	0.120	0.000	0.002	0.000	0.023	0.023	0.436	0.108	0.000	-0.207
31/07/2013	31	3.980	0.000	0.003	1.152	0.028	0.005	0.519	0.519	0.000	-0.188
1/08/2013	32	0.000	0.000	0.000	0.000	0.028	0.019	0.466	0.228	0.000	-0.162
2/08/2013	33	1.990	0.000	0.003	0.000	0.028	0.005	0.429	0.429	0.000	-0.191
3/08/2013	34	0.000	0.000	0.000	0.000	0.037	0.034	0.413	0.228	0.000	-0.255
4/08/2013	35	0.000	2.000	0.000	0.000	0.053	0.013	0.492	0.492	0.000	-0.357
5/08/2013	36	0.000	0.000	0.000	0.000	0.042	0.038	0.329	0.228	0.000	-0.404
6/08/2013	37	0.000	0.000	0.000	0.000	0.046	0.046	0.318	0.175	0.000	-0.469
7/08/2013	38	0.350	0.000	0.007	0.000	0.061	0.061	0.406	0.406	0.000	-0.417
8/08/2013	39	0.000	0.000	0.000	0.000	0.074	0.074	0.401	0.228	0.000	-0.351
9/08/2013	40	0.000	0.000	0.000	0.000	0.064	0.064	0.312	0.175	0.000	-0.299
10/08/2013	41	0.470	0.000	0.009	0.000	0.091	0.091	0.442	0.442	0.000	-0.258
11/08/2013	42	0.000	0.000	0.000	0.000	0.080	0.080	0.328	0.228	0.000	-0.224
12/08/2013	43	1.790	0.000	0.011	0.000	0.085	0.059	0.359	0.359	0.000	-0.197
13/08/2013	44	0.000	0.000	0.000	0.000	0.084	0.082	0.295	0.228	0.000	-0.173

15/08/2013	46	2.450	0.000	0.014	0.000	0.114	0.072	0.381	0.381	0.000	-0.168
16/08/2013	47	0.270	0.000	0.013	0.000	0.098	0.084	0.290	0.228	0.000	-0.157
17/08/2013	48	0.310	0.000	0.018	0.000	0.098	0.098	0.216	0.175	0.000	-0.181
18/08/2013	49	0.870	0.000	0.025	0.000	0.164	0.164	0.272	0.272	0.000	-0.222
19/08/2013	50	0.070	0.000	0.017	0.000	0.139	0.139	0.176	0.176	0.000	-0.229
20/08/2013	51	0.590	0.000	0.033	0.000	0.199	0.199	0.212	0.212	0.000	-0.230
21/08/2013	52	0.280	0.000	0.034	0.000	0.263	0.263	0.224	0.224	0.000	-0.222
22/08/2013	53	0.000	0.000	0.000	0.000	0.332	0.331	0.218	0.175	0.000	-0.208
23/08/2013	54	0.000	3.000	0.000	0.424	0.329	0.232	0.184	0.184	0.000	-0.191
24/08/2013	55	0.000	0.000	0.000	0.000	0.408	0.350	0.195	0.195	0.000	-0.167
25/08/2013	56	1.300	0.000	0.059	0.000	0.314	0.254	0.147	0.147	0.000	-0.174
26/08/2013	57	0.000	0.000	0.000	0.000	0.368	0.362	0.138	0.138	0.000	-0.196
27/08/2013	58	0.350	0.000	0.057	0.000	0.304	0.304	0.123	0.123	0.000	-0.215
28/08/2013	59	0.200	2.500	0.052	0.271	0.432	0.294	0.155	0.155	0.000	-0.215
29/08/2013	60	0.990	0.000	0.067	0.000	0.492	0.307	0.166	0.166	0.000	-0.192
30/08/2013	61	0.060	0.000	0.033	0.000	0.547	0.541	0.168	0.168	0.000	-0.235
31/08/2013	62	0.280	0.000	0.060	0.000	0.547	0.547	0.163	0.163	0.000	-0.302
1/09/2013	63	1.150	0.000	0.074	0.000	0.549	0.526	0.157	0.157	0.000	-0.281
2/09/2013	64	0.020	0.000	0.016	0.000	0.338	0.337	0.087	0.087	0.000	-0.236
3/09/2013	65	0.000	2.500	0.000	0.129	0.477	0.334	0.112	0.112	0.000	-0.205
4/09/2013	66	0.000	0.000	0.000	0.000	0.461	0.393	0.102	0.102	0.000	-0.180
5/09/2013	67	1.490	0.000	0.082	0.000	0.485	0.364	0.117	0.117	0.000	-0.200
6/09/2013	68	0.140	2.000	0.054	0.000	0.535	0.329	0.121	0.121	0.000	-0.222
7/09/2013	69	1.520	0.000	0.084	0.000	0.472	0.287	0.112	0.112	0.000	-0.278
8/09/2013	70	0.000	0.000	0.000	0.000	0.736	0.655	0.151	0.151	0.000	-0.476
9/09/2013	71	0.000	0.000	0.000	0.000	0.596	0.596	0.120	0.120	0.000	-0.529
10/09/2013	72	2.620	0.000	0.088	0.182	0.463	0.340	0.102	0.102	0.000	-0.404
11/09/2013	73	6.630	0.000	0.091	4.990	0.285	0.183	0.065	0.065	0.000	-0.320
12/09/2013	74	0.000	0.000	0.000	0.000	0.606	0.519	0.115	0.115	0.000	-0.418
13/09/2013	75	0.000	0.000	0.000	0.000	0.600	0.600	0.111	0.111	0.000	-0.518
14/09/2013	76	0.000	0.000	0.000	0.000	0.667	0.667	0.121	0.121	0.000	-0.412
15/09/2013	77	2.620	0.000	0.092	0.097	0.544	0.425	0.108	0.108	0.000	-0.310
16/09/2013	78	1.660	0.000	0.091	0.000	0.630	0.433	0.121	0.121	0.000	-0.237
17/09/2013	79	0.000	0.000	0.000	0.000	0.721	0.641	0.124	0.124	0.000	-0.230
18/09/2013	80	0.000	0.000	0.000	0.000	0.834	0.834	0.140	0.140	0.000	-0.306

18/09/2013	80	0.000	0.000	0.000	0.000	0.834	0.834	0.140	0.140	0.000	-0.306
19/09/2013	81	0.000	0.000	0.000	0.000	0.843	0.843	0.142	0.142	0.000	-0.282
20/09/2013	82	0.000	4.000	0.000	1.317	0.756	0.598	0.129	0.129	0.000	-0.223
21/09/2013	83	0.000	0.000	0.000	0.000	0.622	0.558	0.108	0.108	0.000	-0.172
22/09/2013	84	0.000	0.000	0.000	0.000	0.564	0.564	0.100	0.100	0.000	-0.149
23/09/2013	85	1.040	0.000	0.087	0.000	0.228	0.220	0.051	0.051	0.000	-0.151
24/09/2013	86	0.000	0.000	0.000	0.000	0.504	0.502	0.092	0.092	0.000	-0.147
25/09/2013	87	0.000	0.000	0.000	0.000	0.343	0.343	0.064	0.064	0.000	-0.135
26/09/2013	88	0.000	2.500	0.000	0.041	0.592	0.474	0.112	0.112	0.000	-0.129
27/09/2013	89	0.000	0.000	0.000	0.000	0.668	0.604	0.128	0.128	0.000	-0.115
28/09/2013	90	1.700	0.000	0.087	0.000	0.545	0.439	0.116	0.116	0.000	-0.101
29/09/2013	91	0.000	0.000	0.000	0.000	0.535	0.527	0.106	0.106	0.000	-0.104
30/09/2013	92	0.000	0.000	0.000	0.000	0.496	0.496	0.100	0.100	0.000	-0.115
1/10/2013	93	0.000	3.000	0.000	0.456	0.778	0.613	0.159	0.159	0.000	-0.131
2/10/2013	94	0.000	0.000	0.000	0.000	0.696	0.626	0.145	0.145	0.000	-0.122
3/10/2013	95	0.000	0.000	0.000	0.000	0.678	0.678	0.143	0.143	0.000	-0.112
4/10/2013	96	0.000	0.000	0.000	0.000	0.573	0.573	0.123	0.123	0.000	-0.123
5/10/2013	97	0.000	3.000	0.000	0.354	0.668	0.543	0.146	0.146	0.000	-0.121
6/10/2013	98	0.000	0.000	0.000	0.000	0.665	0.602	0.148	0.148	0.000	-0.108
7/10/2013	99	0.000	0.000	0.000	0.000	0.668	0.668	0.151	0.151	0.000	-0.090
8/10/2013	100	2.230	0.000	0.081	0.000	0.514	0.423	0.130	0.130	0.000	-0.090
9/10/2013	101	0.000	0.000	0.000	0.000	0.515	0.488	0.120	0.120	0.000	-0.089
10/10/2013	102	0.000	0.000	0.000	0.000	0.563	0.563	0.134	0.134	0.000	-0.082
11/10/2013	103	1.090	0.000	0.077	0.000	0.778	0.778	0.199	0.199	0.000	-0.089
12/10/2013	104	0.000	0.000	0.000	0.000	0.872	0.872	0.214	0.214	0.000	-0.090
13/10/2013	105	0.000	0.000	0.000	0.000	0.816	0.805	0.204	0.175	0.000	-0.082
14/10/2013	106	0.000	0.000	0.000	0.000	0.694	0.637	0.176	0.147	0.000	-0.073
15/10/2013	107	0.000	0.000	0.000	0.000	0.738	0.617	0.191	0.130	0.000	-0.065
16/10/2013	108	0.000	0.000	0.000	0.000	0.771	0.578	0.203	0.117	0.000	-0.058
17/10/2013	109	0.000	0.000	0.000	0.000	0.828	0.548	0.221	0.108	0.000	-0.052
18/10/2013	110	0.000	0.000	0.000	0.000	0.841	0.484	0.229	0.100	0.000	-0.046

ISIAMOD soil water balance results

DAILY SOIL WATER BALANCE (cm)

Date	Days after planting	Rain depth	Irrig. depth	Interc. losses	Runoff	Potential ET		Actual ET		Actual percol.	Deep
						Evapo.	Transp.	Evapo.	Transp.		
15/ 7/2013	0	8.65	.00	.00	3.14	.426	.000	.426	.000	.426	.00
16/ 7/2013	1	.64	.00	.00	.00	.398	.000	.398	.000	.398	.00
17/ 7/2013	2	.00	.00	.00	.00	.468	.000	.267	.000	.267	.00
18/ 7/2013	3	.20	.00	.00	.00	.421	.000	.210	.000	.210	.00
19/ 7/2013	4	2.80	.00	.00	.13	.323	.002	.323	.002	.325	.00
20/ 7/2013	5	.00	.00	.00	.00	.351	.003	.229	.003	.232	.00
21/ 7/2013	6	.14	.00	.00	.00	.373	.004	.208	.004	.212	.00
22/ 7/2013	7	.00	.00	.00	.00	.422	.006	.141	.006	.147	.00
23/ 7/2013	8	.00	.00	.00	.00	.472	.009	.086	.009	.095	.00
24/ 7/2013	9	1.50	.00	.00	.00	.416	.005	.416	.005	.420	.00
25/ 7/2013	10	.00	.00	.00	.00	.373	.008	.206	.008	.214	.00
26/ 7/2013	11	.22	.00	.00	.00	.442	.011	.250	.011	.260	.00
27/ 7/2013	12	.00	.00	.00	.00	.395	.014	.117	.014	.131	.00
28/ 7/2013	13	.00	.00	.00	.00	.320	.014	.055	.014	.068	.00
29/ 7/2013	14	.00	.00	.00	.00	.391	.019	.044	.019	.063	.00
30/ 7/2013	15	.40	.00	.00	.00	.403	.017	.198	.017	.216	.00
31/ 7/2013	16	5.33	.00	.00	1.09	.452	.016	.452	.016	.468	.00
1/ 8/2013	17	1.61	.00	.00	.00	.361	.017	.361	.017	.378	.00
2/ 8/2013	18	1.99	.00	.01	.01	.311	.019	.311	.019	.330	.00
3/ 8/2013	19	.00	.00	.00	.00	.368	.039	.245	.039	.285	.00

DAILY SOIL WATER BALANCE (cm) cont'.

Date	Days after planting	Rain depth	Irrig. depth	Interc. losses	Runoff	Potential		Actual		Actual ET	Deep percol.
						Evapo.	Transp.	Evapo.	Transp.		
4/ 8/2013	20	.00	2.00	.00	.00	.391	.039	.391	.039	.430	.00
5/ 8/2013	21	.00	.00	.00	.00	.222	.028	.222	.028	.250	.00
6/ 8/2013	22	.00	.00	.00	.00	.408	.080	.311	.080	.390	.00
7/ 8/2013	23	.53	.00	.02	.00	.345	.069	.338	.069	.407	.00
8/ 8/2013	24	.00	.00	.00	.00	.405	.285	.250	.285	.384	.00
9/ 8/2013	25	.00	.00	.00	.00	.313	.253	.109	.253	.261	.00
10/ 8/2013	26	.76	.00	.03	.00	.345	.133	.345	.133	.478	.00
11/ 8/2013	27	.00	.00	.00	.00	.347	.219	.218	.219	.437	.00
12/ 8/2013	28	2.44	.00	.04	.05	.263	.158	.263	.158	.421	.00
13/ 8/2013	29	.00	.00	.00	.00	.259	.237	.186	.237	.422	.00
14/ 8/2013	30	.00	.00	.00	.00	.137	.173	.071	.173	.244	.00
15/ 8/2013	31	3.18	.00	.05	.21	.209	.244	.209	.244	.453	.26
16/ 8/2013	32	.40	.00	.06	.00	.185	.269	.185	.269	.453	.00
17/ 8/2013	33	.38	.00	.06	.00	.135	.354	.135	.354	.379	.00
18/ 8/2013	34	1.07	.00	.07	.00	.162	.463	.162	.463	.525	.37
19/ 8/2013	35	.07	.00	.00	.00	.064	.190	.053	.190	.243	.00
20/ 8/2013	36	.60	.00	.08	.00	.097	.330	.097	.330	.427	.00
21/ 8/2013	37	.46	.00	.08	.00	.115	.479	.115	.479	.594	.00
22/ 8/2013	38	.00	.00	.00	.00	.086	.441	.075	.441	.516	.00
23/ 8/2013	39	.00	3.00	.00	.00	.067	.403	.067	.403	.470	1.59
24/ 8/2013	40	.00	.00	.00	.00	.060	.425	.060	.425	.485	.00

DAILY SOIL WATER BALANCE (cm) cont'.

Date	Days after planting	Rain depth	Irrig. depth	Interc. losses	Runoff	Potential		Actual		Actual ET	Deep percol.
						Evapo.	Transp.	Evapo.	Transp.		
25/ 8/2013	41	1.94	.00	.09	.00	.059	.485	.059	.485	.543	.96
26/ 8/2013	42	.00	.00	.00	.00	.050	.480	.047	.480	.527	.00
27/ 8/2013	43	.55	.00	.09	.00	.044	.477	.044	.476	.521	.00
28/ 8/2013	44	.34	2.50	.09	.00	.041	.494	.041	.641	.535	1.61
29/ 8/2013	45	1.26	.00	.09	.00	.038	.671	.038	.671	.538	.67
30/ 8/2013	46	.06	.00	.00	.00	.042	.600	.040	.599	.639	.00
31/ 8/2013	47	.28	.00	.09	.00	.031	.585	.031	.584	.516	.00
1/ 9/2013	48	.00	.00	.00	.00	.031	.503	.030	.498	.528	.00
2/ 9/2013	49	.00	.00	.00	.00	.022	.390	.021	.386	.407	.00
3/ 9/2013	50	.00	2.50	.00	.00	.028	.504	.028	.504	.531	.05
4/ 9/2013	51	.00	.00	.00	.00	.030	.567	.030	.566	.597	.00
5/ 9/2013	52	1.88	.00	.10	.00	.025	.475	.025	.475	.500	.68
6/ 9/2013	53	.18	2.00	.10	.00	.028	.564	.028	.564	.593	1.58
7/ 9/2013	54	2.00	.00	.10	.01	.024	.488	.024	.488	.512	1.33
8/ 9/2013	55	.00	.00	.00	.00	.029	.702	.028	.702	.630	.00
9/ 9/2013	56	.00	.00	.00	.00	.029	.616	.028	.613	.641	.00
10/ 9/2013	57	2.62	.00	.10	.07	.024	.504	.024	.504	.528	.66

DAILY SOIL WATER BALANCE (cm) cont'.

Date	Days after planting	Rain depth	Irrig. depth	Interc. losses	Runoff	Potential		Actual		Actual ET	Deep percol.
						Evapo.	Transp.	Evapo.	Transp.		
11/ 9/2013	58	6.63	.00	.10	1.76	.020	.421	.020	.421	.441	4.25
12/ 9/2013	59	1.41	.00	.10	.00	.024	.517	.024	.517	.541	.87
13/ 9/2013	60	.00	.00	.00	.00	.026	.557	.025	.557	.582	.00
14/ 9/2013	61	.00	.00	.00	.00	.025	.555	.024	.554	.577	.00
15/ 9/2013	62	2.62	.00	.10	.07	.027	.603	.027	.603	.630	.75
16/ 9/2013	63	2.30	.00	.10	.03	.029	.632	.029	.632	.660	1.54
17/ 9/2013	64	.00	.00	.00	.00	.031	.698	.030	.697	.727	.00
18/ 9/2013	65	.00	.00	.00	.00	.029	.638	.027	.632	.659	.00
19/ 9/2013	66	.00	.00	.00	.00	.031	.697	.028	.674	.702	.00
20/ 9/2013	67	.00	4.00	.00	.00	.027	.602	.027	.602	.629	1.25
21/ 9/2013	68	.00	.00	.00	.00	.021	.578	.021	.578	.500	.00
22/ 9/2013	69	.00	.00	.00	.00	.021	.469	.020	.469	.489	.00
23/ 9/2013	70	1.45	.00	.10	.00	.020	.423	.020	.423	.443	.00
24/ 9/2013	71	.00	.00	.00	.00	.022	.478	.021	.478	.399	.00
25/ 9/2013	72	.00	.00	.00	.00	.035	.510	.034	.509	.543	.00
26/ 9/2013	73	.00	2.50	.00	.00	.053	.631	.053	.631	.684	.88
27/ 9/2013	74	.00	.00	.00	.00	.048	.475	.048	.475	.523	.00
28/ 9/2013	75	1.70	.00	.09	.00	.066	.541	.066	.541	.607	.46
29/ 9/2013	76	.00	.00	.00	.00	.084	.570	.078	.570	.648	.00
30/ 9/2013	77	.00	.00	.00	.00	.085	.484	.072	.483	.555	.00

DAILY SOIL WATER BALANCE (cm) end file.

Date	Days after planting	Rain depth	Irrig. depth	Interc. losses	Runoff	Potential		Actual		Actual ET	Deep percol.
						Evapo.	Transp.	Evapo.	Transp.		
1/10/2013	78	.00	3.00	.00	.00	.111	.499	.111	.499	.610	1.19
2/10/2013	79	.00	.00	.00	.00	.119	.429	.119	.429	.547	.00
3/10/2013	80	.00	.00	.00	.00	.155	.466	.135	.466	.600	.00
4/10/2013	81	.00	.00	.00	.00	.166	.422	.121	.422	.543	.00
5/10/2013	82	.00	3.00	.00	.00	.187	.328	.187	.328	.515	.81
6/10/2013	83	.00	.00	.00	.00	.218	.287	.218	.287	.505	.00
7/10/2013	84	.00	.00	.00	.00	.241	.267	.184	.267	.451	.00
8/10/2013	85	2.20	.00	.04	.02	.493	.493	.493	.493	.316	.85
9/10/2013	86	.00	.00	.00	.00	.302	.136	.240	.136	.375	.00
10/10/2013	87	.00	.00	.00	.00	.386	.380	.377	.370	.297	.00

APPENDIX C

The FAO-56 PM (Allen et al 1998)equation with its parameters details are:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\,[900/(T+273)]u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \quad \text{……(1)}$$

- **Atmospheric Pressure (P)**

The atmospheric pressure is the pressure exerted by the weight of the earth's atmosphere. The equation is used for calculating atmosphere pressure in FAO 56 Penman-Monteith equation is as follows:

$P = 101.3 - 0.01055H$ …….(2)

Where: H is the elevation of above sea level.

- **Psychometric Constant (γ)**

The psychometric constant is given by

$\gamma = [C_p * P]/[0.622\lambda]$ ……..……..(3)

C_p is specific heat of water at constant pressure (0.001013KJ/Kg ^oC)

$\lambda = 2.5 - 2.36 * 10^{-3} * T$ ……(4)

- **Mean Saturation Vapour Pressure (E_s)**

Saturation vapour pressure is related to air temperature; it can be calculated from the air temperature. The relationship is expressed by:

$$e^{\circ}(T) = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \quad \text{……(5)}$$

The equation is used for the calculation of saturation vapour pressure is given by:

$$e_s = \frac{e^{\circ}(T_{max}) + e^{\circ}(T_{min})}{2} \quad \text{…… (6)}$$

Or, from the graph below

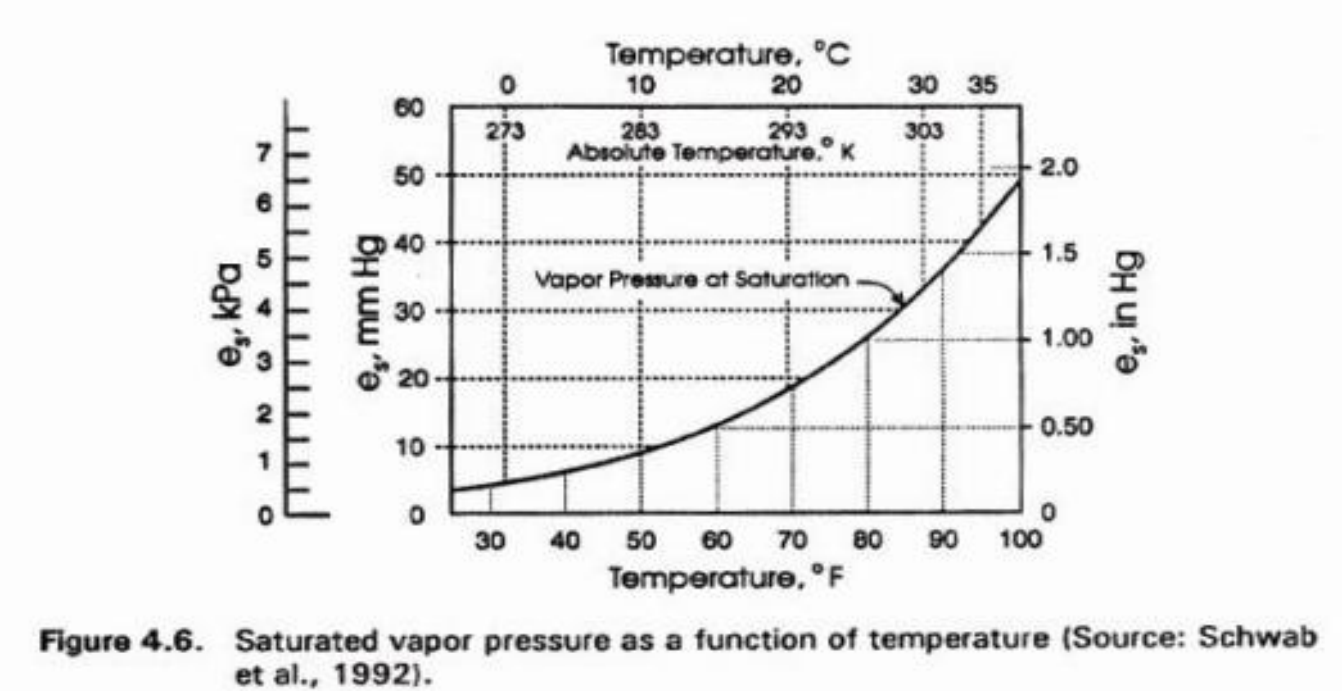


Figure 4.6. Saturated vapor pressure as a function of temperature (Source: Schwab et al., 1992).

- **Slop of Saturation Vapour Pressure Curve (Δ)**

The slop of the saturation vapour pressure curve at a given temperature is given by:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \quad \text{… ……(7)}$$

or

$$\Delta = 0.200\,[0.00738T + 0.8072]^7 - 0.000116 \quad \text{……(7b)}$$

- **Net Radiation (Rn)**

The Net radiation is the difference between the incoming net short wave radiation and the outgoing net long wave radiation and is expressed as:

$$R_n = R_{ns} - R_{nl} \quad \ldots\ldots (8)$$

- **Net short wave radiation (Rns)**

Net short wave radiation resulting from the balance between incoming and reflected solar radiation is given by

$$R_{ns} = (1-\alpha)R_s \ldots\ldots (9)$$

- **Solar radiation (Rs)**

Solar radiation is calculated from the following equation:

$$R_s=(0.25+0.5\ n/N\ R_a) \quad \ldots\ldots (10)$$

- **Net long wave radiation (Rnl)**

The equation for the calculation of net long wave radiation is given by:

$$R_{nl} = \sigma\left[\frac{T_{max}K^4 + T_{min}K^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad \ldots\ldots (11)$$

- **Clear-sky Solar radiation (Rso)**

The equation clear- sky solar radiation is given by:

$$R_{so}= (0.75 + 2\ l0^{-5}z)R_a \ldots\ldots (12)$$

- **Soil Heat Flux (G)**

  For day and ten-day periods:

  As the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it may be ignored and thus: $G_{day} = 0$

- **For monthly periods:** $G_{month,\,i} = 0.14\,(T_{month,\,i} - T_{month,\,i-1})$ ……..(13)

- **Wind Speed**

  The measurement of wind at 2m height is taken as the standard to calculate reference crop evapotranspiration. But if it is not measured at 2m height, then it is calculated at 2m height by the following equation.

CONVERSION FACTOR (CF) OF THE LYSIMETER

The conversion factor of the lysimeter used to convert changed in weight of the lysimeter due to loss or gain of water in the lysimeter. From the relationship of water density given by $\text{volume} = \frac{\text{mass }()}{\text{density}}$, and density of water is 1.0 g/cm^3. Therefore, $= mass$, and $volume = area \times heigth$ (W_h). This implies that,

$\text{heigth}(W_h) = \frac{\text{volume or mass (W)}}{\text{area}}$. The area of the lysimeter is 1320.8 cm^2 and therefore $\text{heigth}(W_h) = \frac{\text{mass (W)}}{1320.8}$ or $(W_h) = \text{CF} * \text{W}.$

where: $\text{CF} = \frac{1}{1320.8} = 0.000757$